NIF Diagnostics: now and in the future

Presentation to
Workshop on Science of Fusion Ignition on NIF
May 23, 2012

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LLNL-PRES-558191

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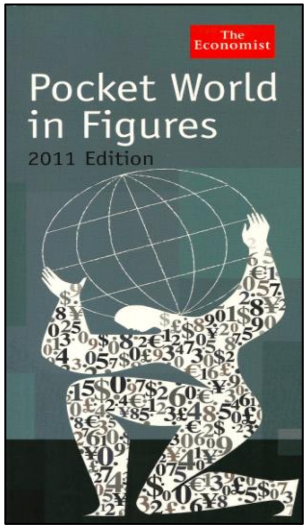
NIF Diagnostics in Figures



- > 50 Diagnostic Systems – and growing
- ~200 people (~160 at LLN), $260M since 2006
- 12 institutions, 4 countries
- ~3 calibration centers

LLNL staff: many others not shown

- Major infrastructure for diagnostic operation
- Active scientific diagnostic community
  - — Developed existing systems at NTS, Nova, OMEGA or Z

NIF diagnostic program spans 12 institutions in four countries

LLNL
- FABS,NBI
- Dante I & II
- VISAR
- DISC
- RAGS
- hGXI
- ARIANE
- DIXI
- NAD

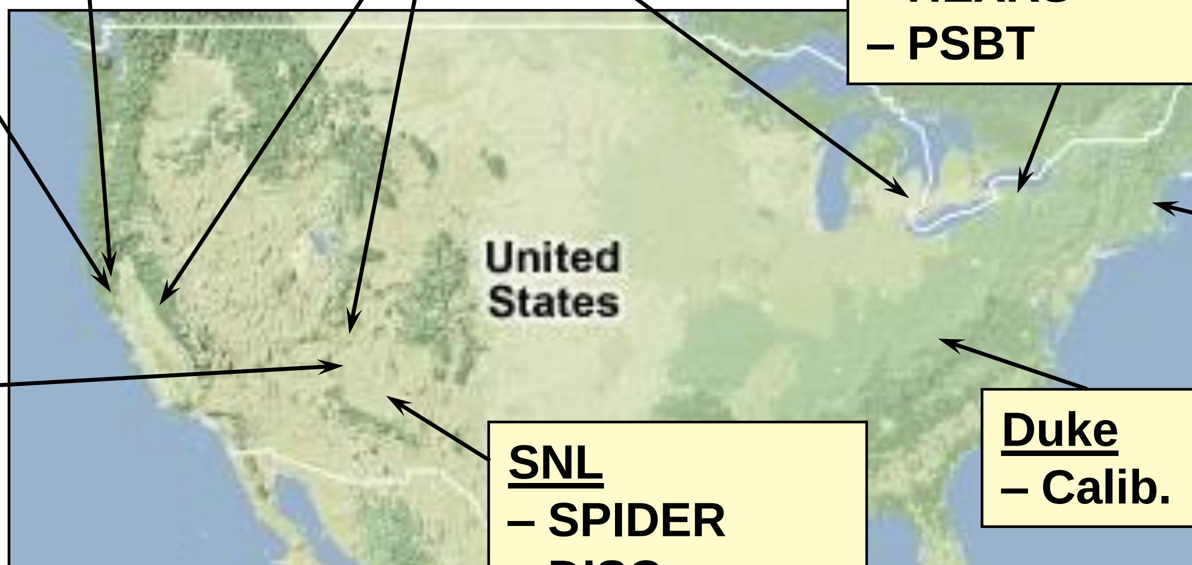
LBNL
- Calibration
- Rad. Chem.

NSTec
- Calibration
- NToF

U of M.
- HEMPI

LLE
- NToF
- 4ω fidu system
- MRS, NADS
- SPBT
- HEXRS
- PSBT

AWE
- FFLEX



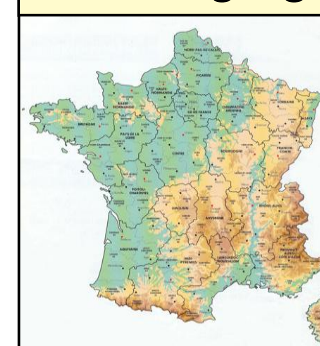
MIT
- MRS
- WRF
- PTOF

LANL
- GXD
- γ burn
- Rad. Chem. II
- n imaging

SNL
- SPIDER
- DISC
- NAD (Cu)
- NToF
- RAGS

Duke
- Calib.

CEA
- N imaging



GSI
-Furlong.

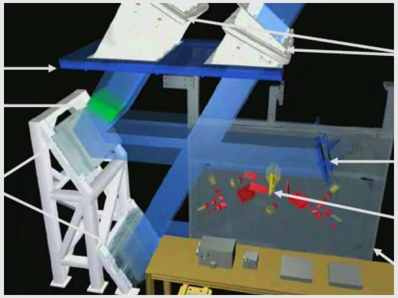
Major infrastructure for operation, data certification, analysis and archiving of NIF Diagnostics

- More than 50% of diagnostics run every shot
- Major set up set up/controls effort ~13,000 parameters/1000 control points
- Maintain configuration control of thousands of diagnostic parameters
- Reliability ~95%
- ~60 analysis algorithms, 600 low level modules using modern software
- Data archiving infrastructure available to all users

Timescale for development: ”simple” ~1 year, complex multi-year

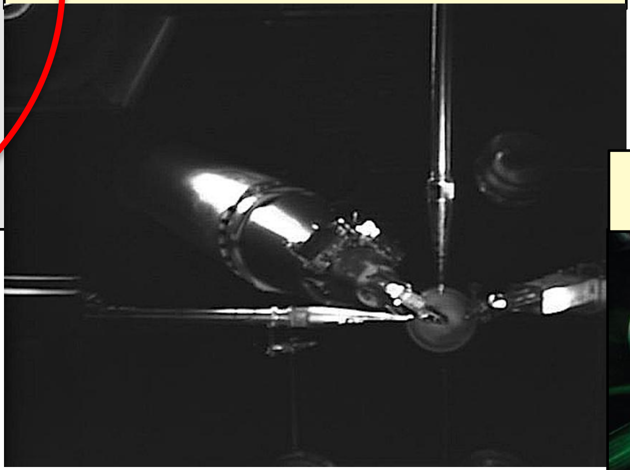
Road map for the talk

Hohlraum Energetics

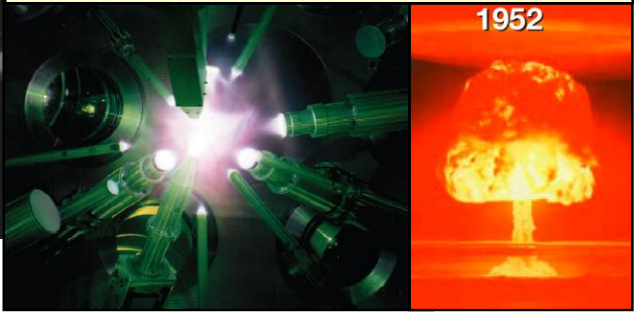


FABS31 on NIF

Implosion phase



Assembly, burn phase



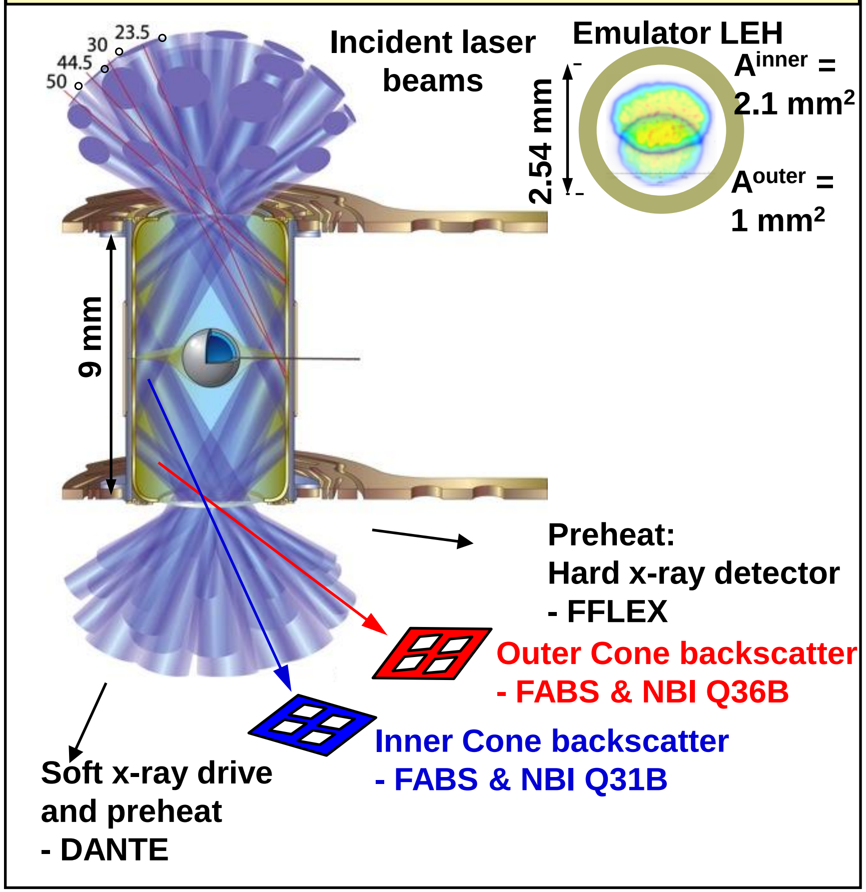
Diagnostics of Hohlraum Conditions

	Attribute	Method	Acronym	Operational
Back- scatter	Into lenses		FABS 50,30	
	Near lenses		NBI 50,30,23.5	
	Other Scatt. Light		ScCal	
Hohlraum x-ray	Soft x-ray P_ν(time)	LEH*, 18 channels	Dante1 & 2	
	Spectrum	Grating		
	Spectrum	Crystal		
	r_{LEH*}	pinhole	SXI-U, SX-IL	
	r_{LEH} (time)			
	Hard x-ray P_ν(time)	filter, flour.	FFLEX	
	Hard x-ray image	pinhole	eHXI	
Hohlraum n_e,T		3ω, 4ω Thomson		
Low n_e	Optical probe	phase, Faraday	OISP	
	Gated optical imager		GOI	

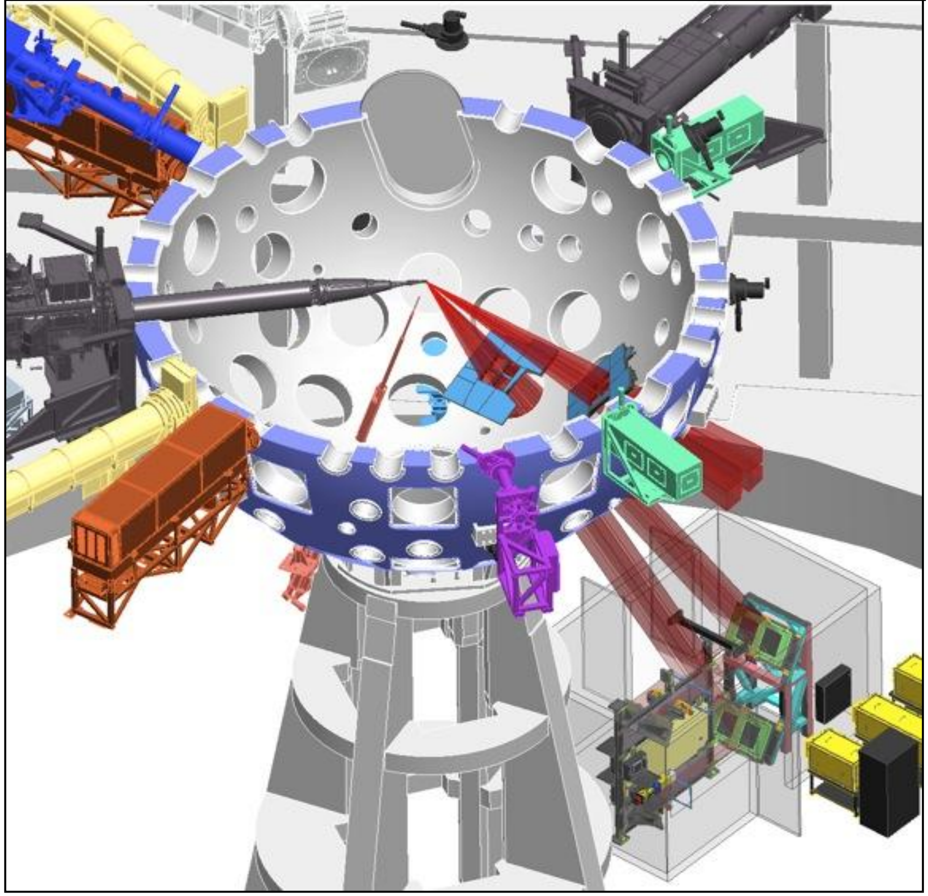
*LEH- laser entrance hole

The backscatter measurement is important for quantifying the energetics aspects of ignition hohlraums

Hohlraum heated by 192 beams emulating ignition conditions

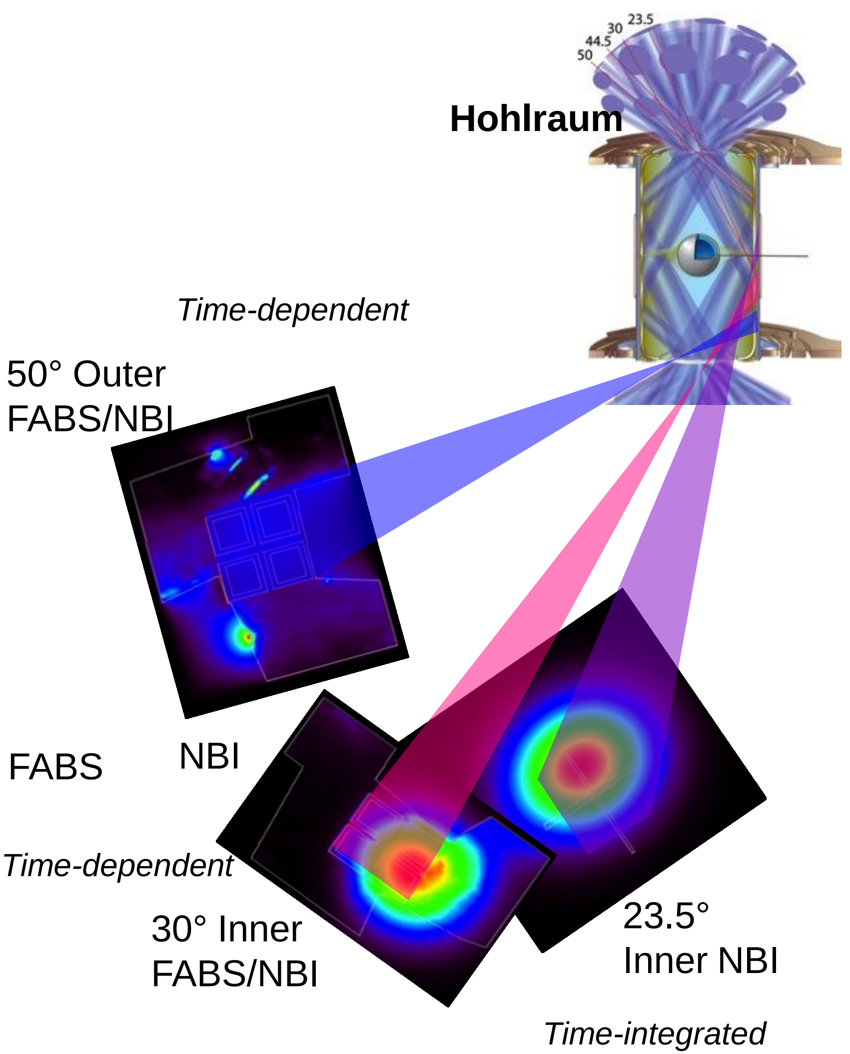


Backscatter instruments (FABS / NBI) are installed on two/three beam quads

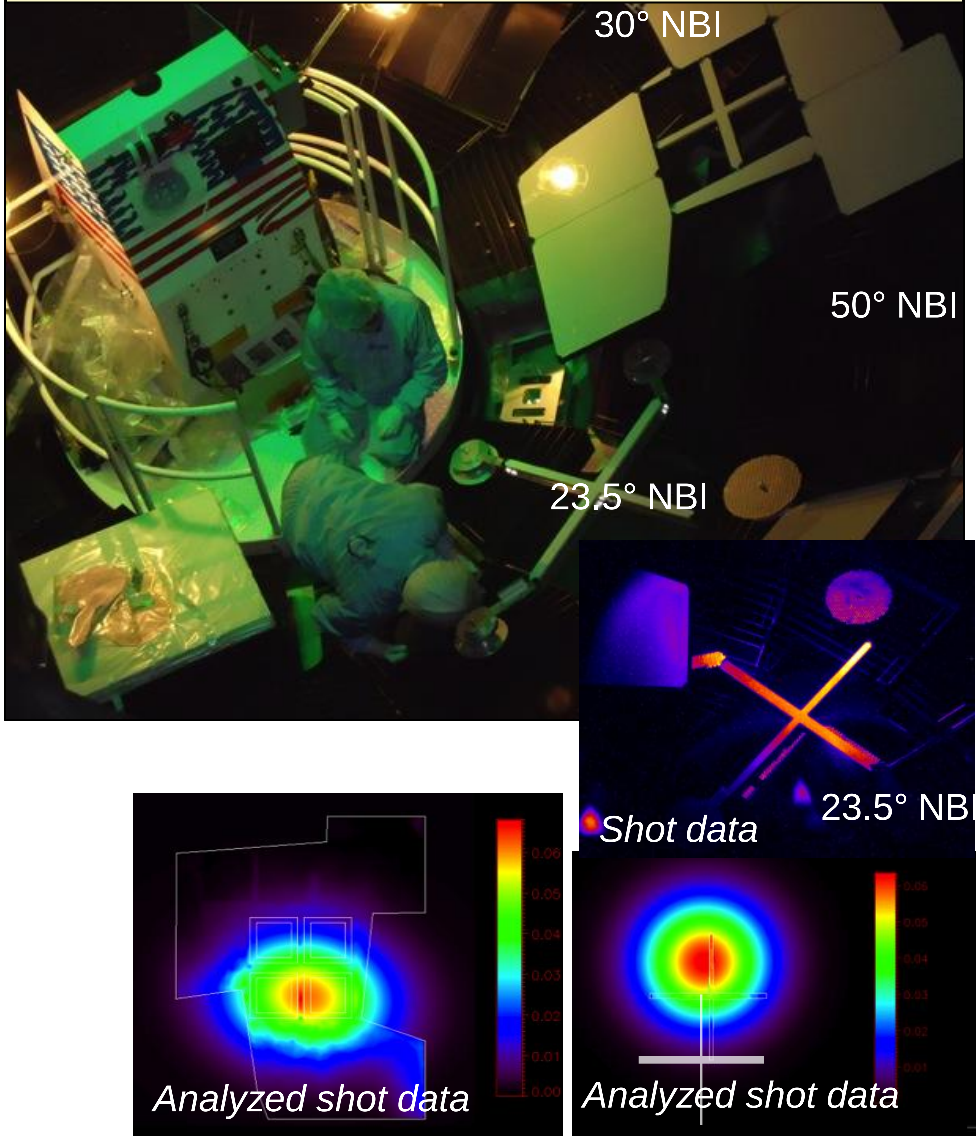


Full Aperture Back-Scattering (FABS) is measured on two Quads, Near Backscatter Imaging(NBI) on 3 Quads

Backscatter is measured on 3 quads

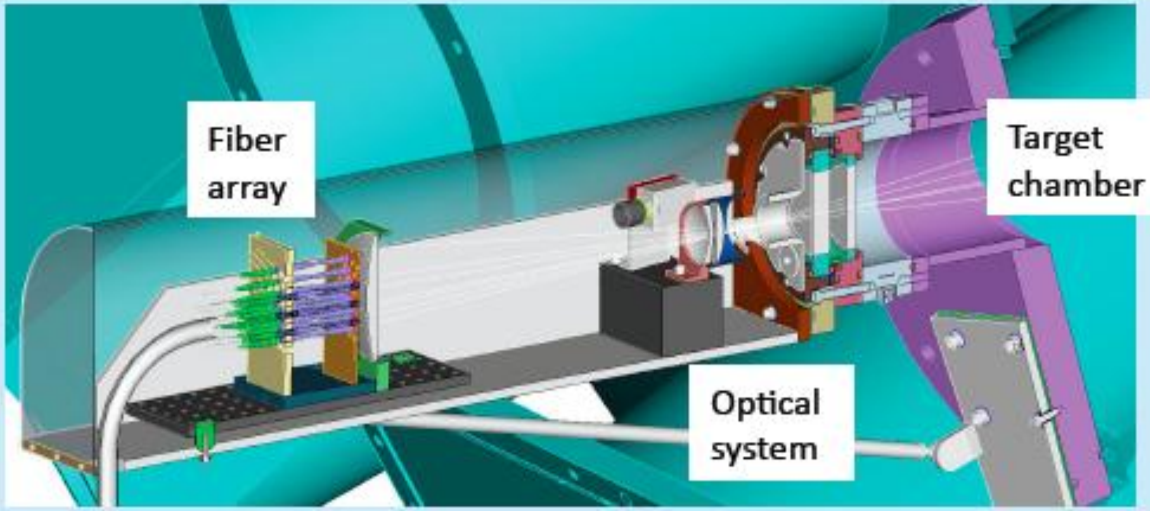


Chamber view

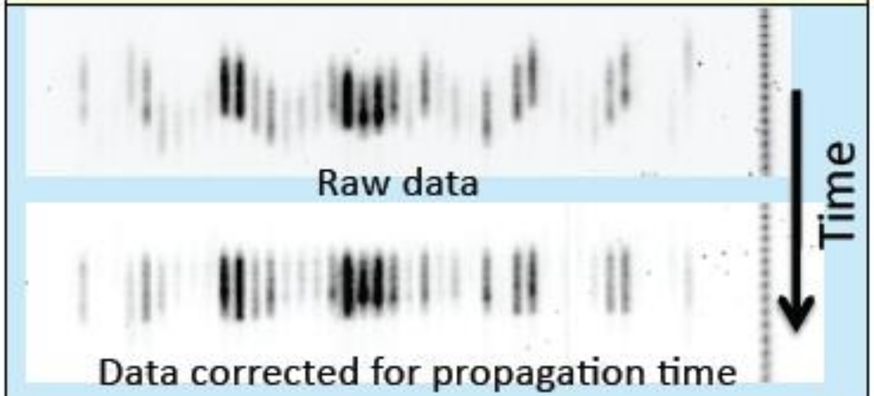


Time-resolved NBI utilizes 40 fibers and a streak camera

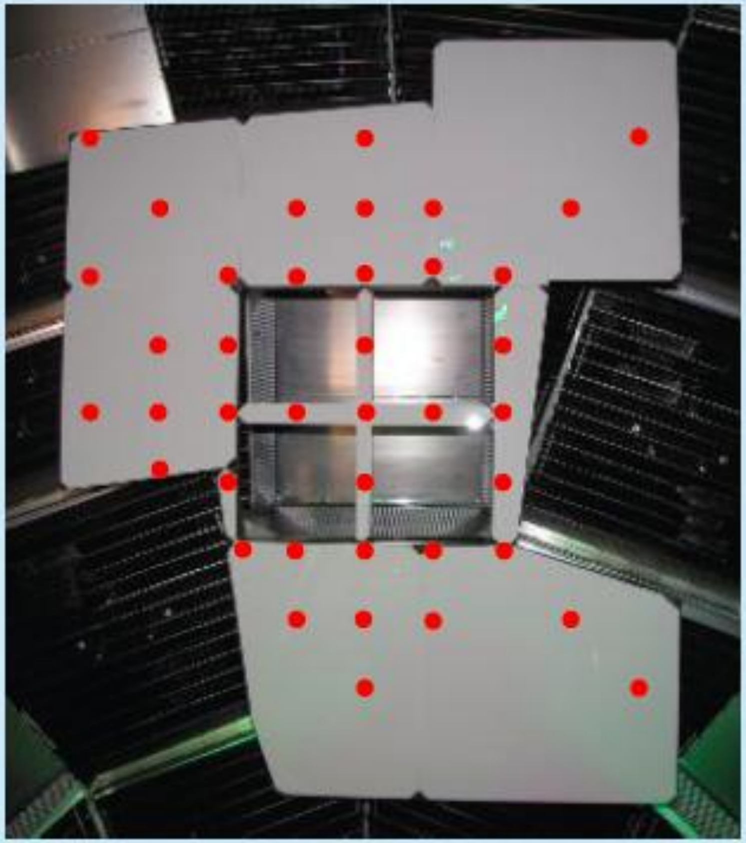
Sketch of NBI-time-resolved system



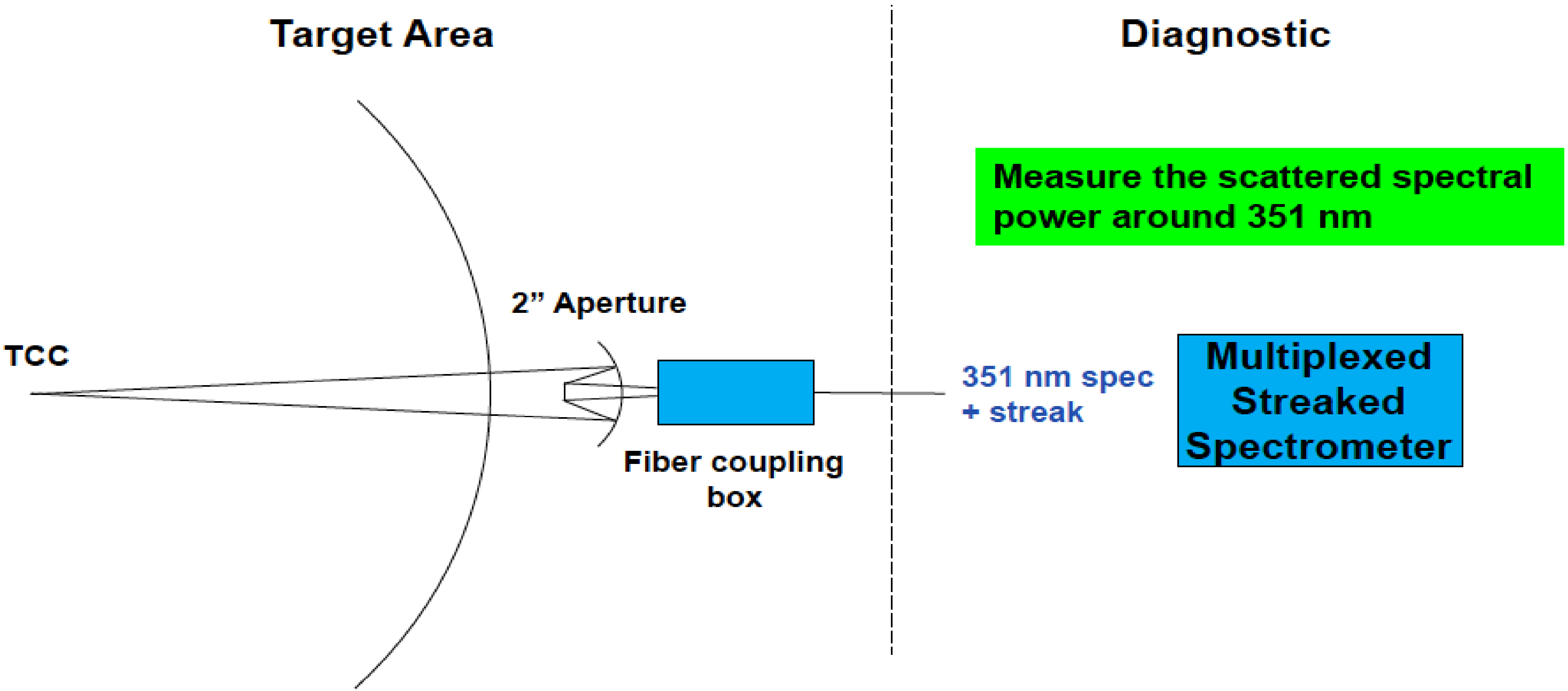
Fiber streaks



Scatter plate with fiber views



For Polar Direct Drive a set of small absolutely calibrated collectors will couple light into fibers at 10–20 locations to be determined



The required number and locations of the detectors are currently being worked out using 3D CBET modeling

X-rays in Hohlraum

	Attribute	Method	Acronym	Operational
Back- scatter	Into lenses		FABS 50,30	
	Near lenses		NBI 50,30,23.5	
	Other Scatt. Light		ScCal	
Hohlraum x-ray	Soft x-ray P_ν(time)	LEH*, 18 channels	Dante1 & 2	
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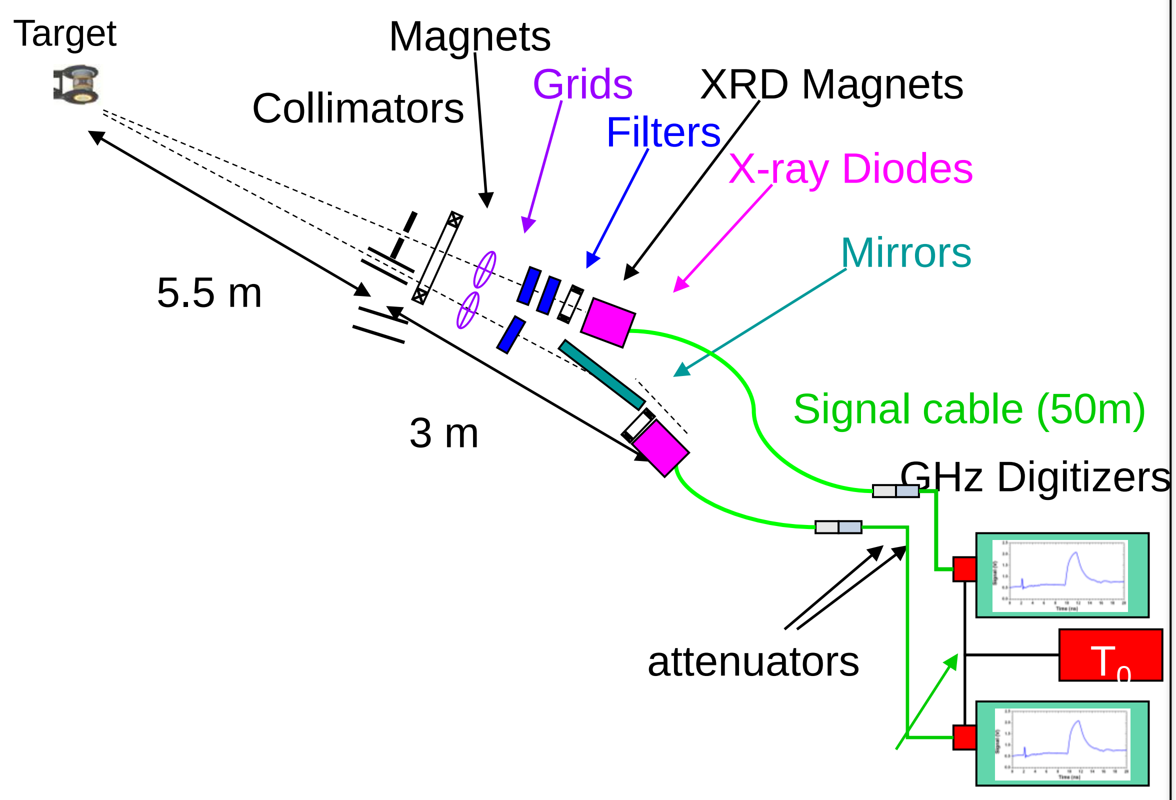
Low n_e	Optical probe	phase, Faraday	OISP	
	Gated optical imager		GOI	

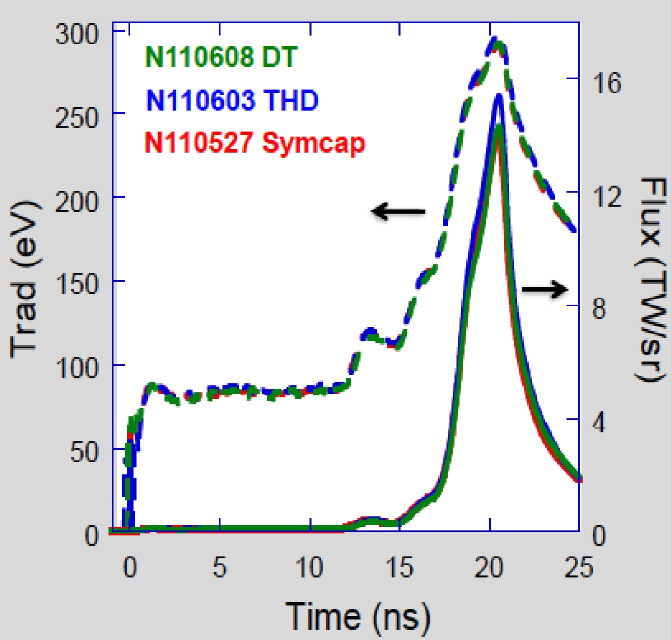
*LEH- laser entrance hole

Two time-resolved 18 diode arrays- Dantes- accurate measurement of the x-ray power through the LEH

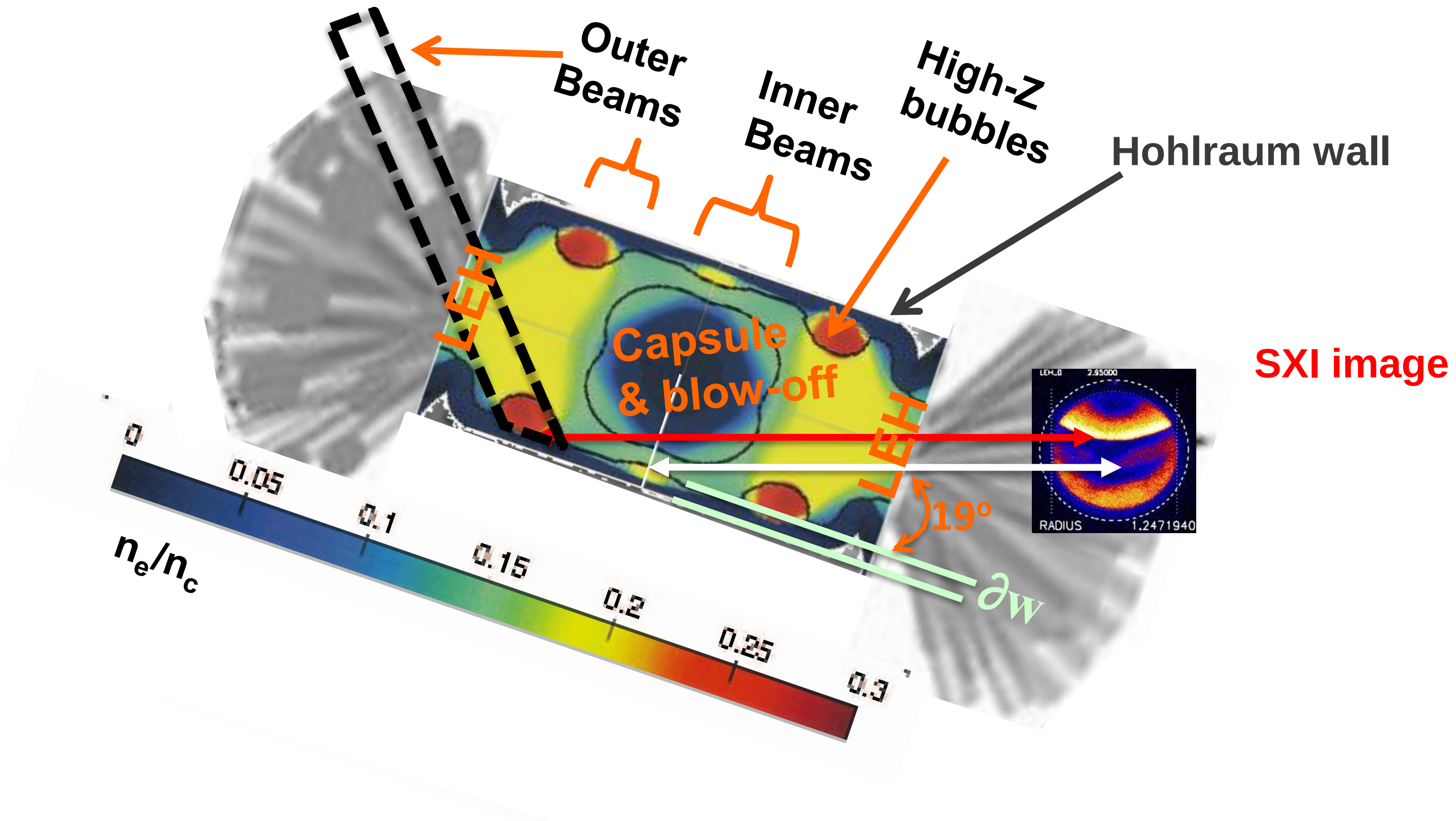
Components of two channels of DANTE



Dante Flux was comparable to the previous THD experiment



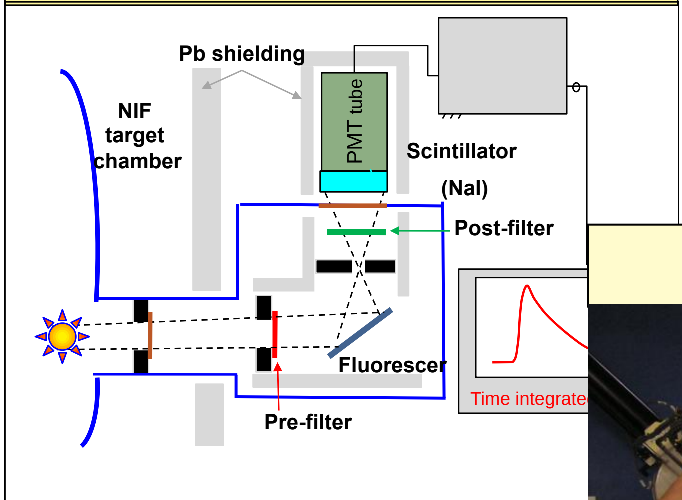
Static x-ray imager uses hohlraum wall to back light the laser entrance hole (LEH) closure



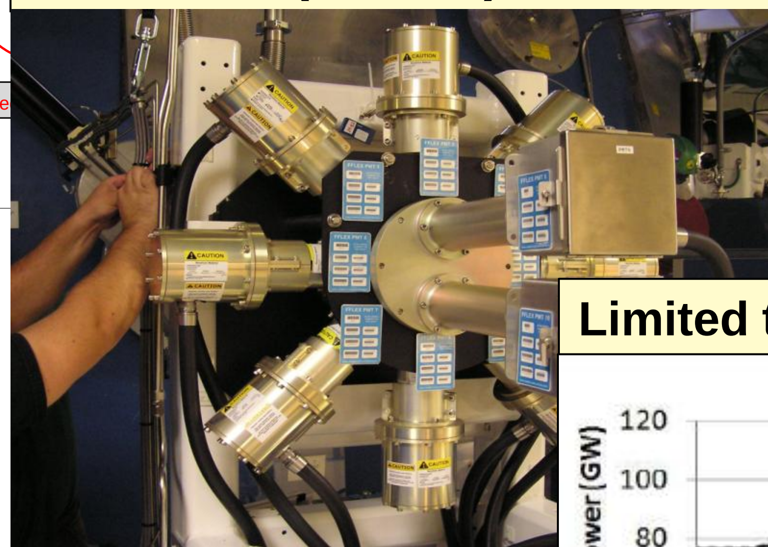
Measured LEH closure of ~ 30% and Dante gives a $T_{rad}(t)$

FFLEX measures hard x-rays <200keV produced by hot electrons Au bremsstrahlung

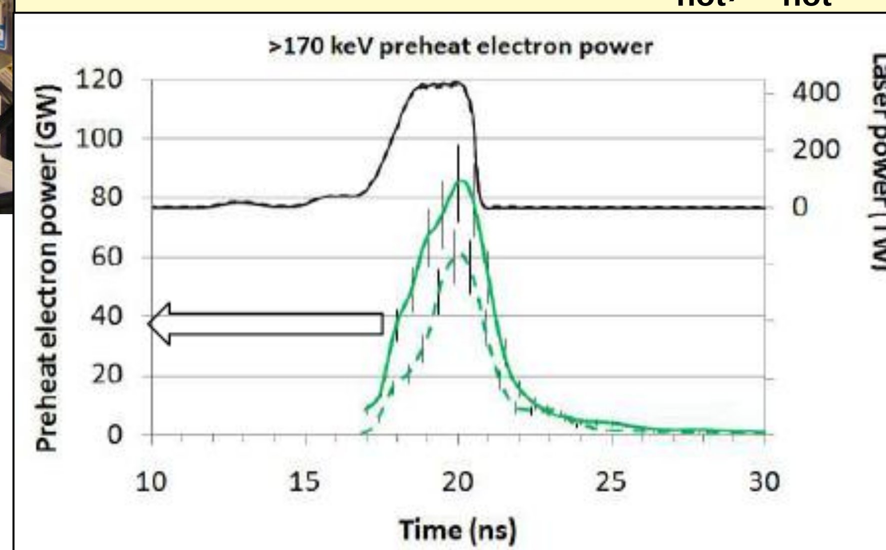
Original FFLEX channel layout (8 channels)



FFLEX (90, 110) on NIF

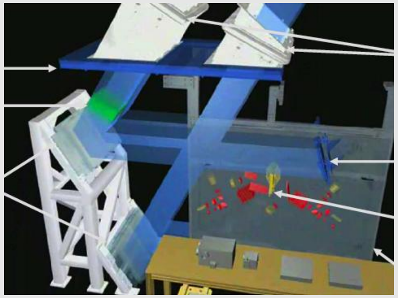


Limited time resolution on T_{hot}, F_{hot}



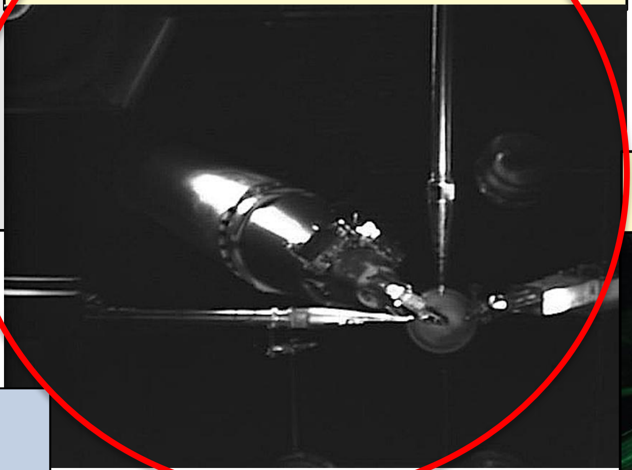
Road map

Hohlraum Energetics

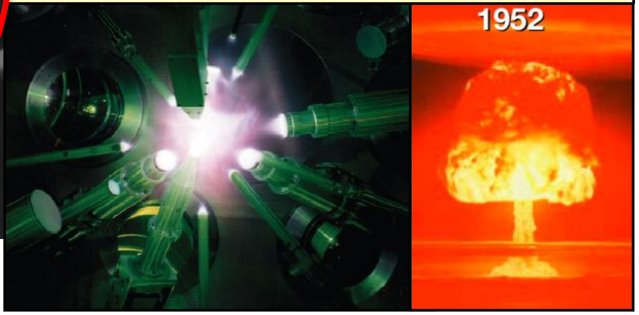


FABS31 on NIF

Implosion phase



Assembly, burn phase



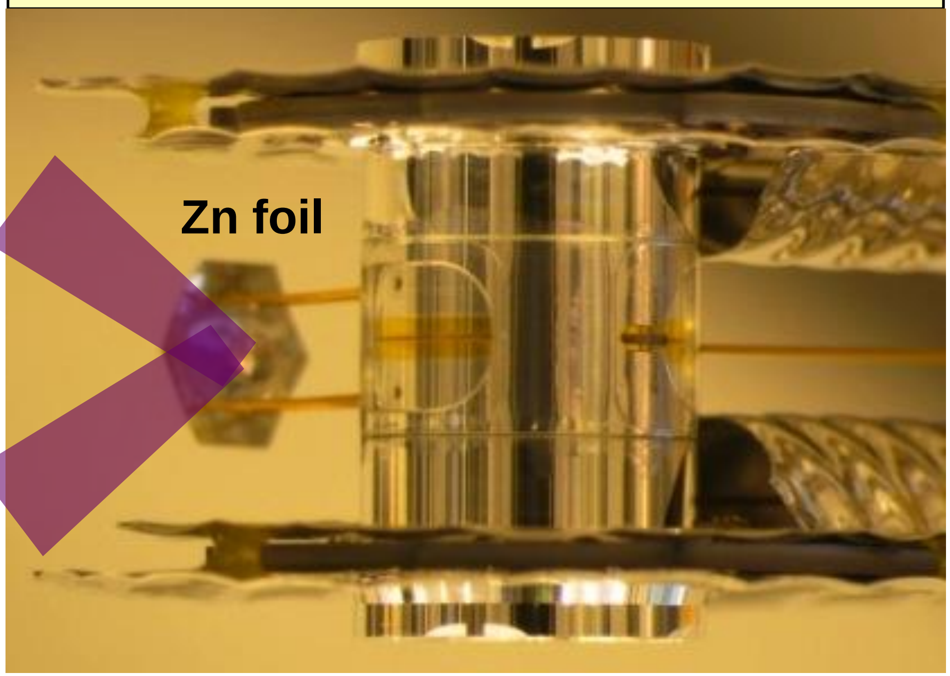
How are we doing?
— Good global measurements
— LEH radius(t)?
— n(r,t), T(r,t) ?

Diagnostics of the ablator and fuel implosion phase

-	Attribute	Method	Acronym	Operational
Shell r(time)	Shell $v_{imp,}\delta x$	Pinhole backlighting	X-ray streak:DISC	
	Symmetry P_n, Y_m	Pinhole imaging	X-ray gating: GXD, hGXI	
	Hi Res δx~ 3 μm	X-ray optic	NIF Chandra	
	DT $v_{imp}/\delta x$	X-ray refraction	X-ray streak-DISC	
Shock (time)	Shock timing	v_{shock}(time)	VISAR, SOP	
	Shock Symmetry	$v_{shock}(t,\theta)$	mVISAR	
	Shock roughness	2D spatial	OFVRC	
Interval	Bang time	X-ray flash	Gated imagers, SPBT	
		X_ray flash	SPIDER- streak	
		γ flash- Cerenkov	GRH, nTOF	
		Protons flash	Mag. pToF	

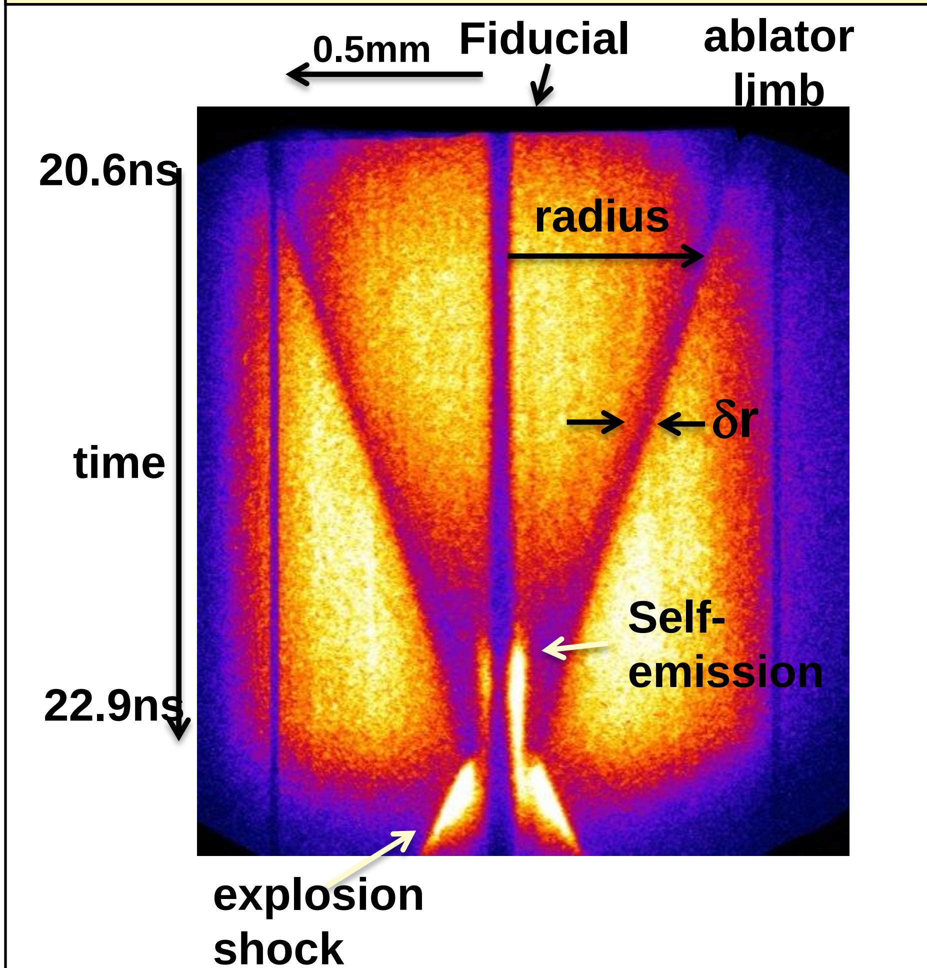
Backlit streaked radiography of imploding plastic ablator, but imaged with a slit

Capsule backlit by x-rays produced by 2 Quads , 50 kJ



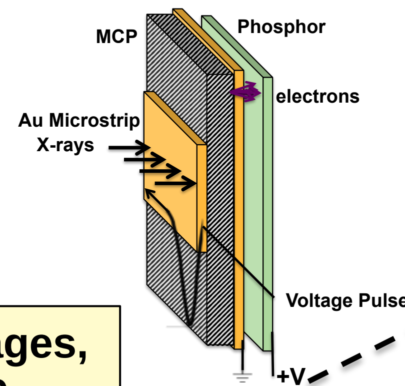
Slit to 10μm resolving δr(time)

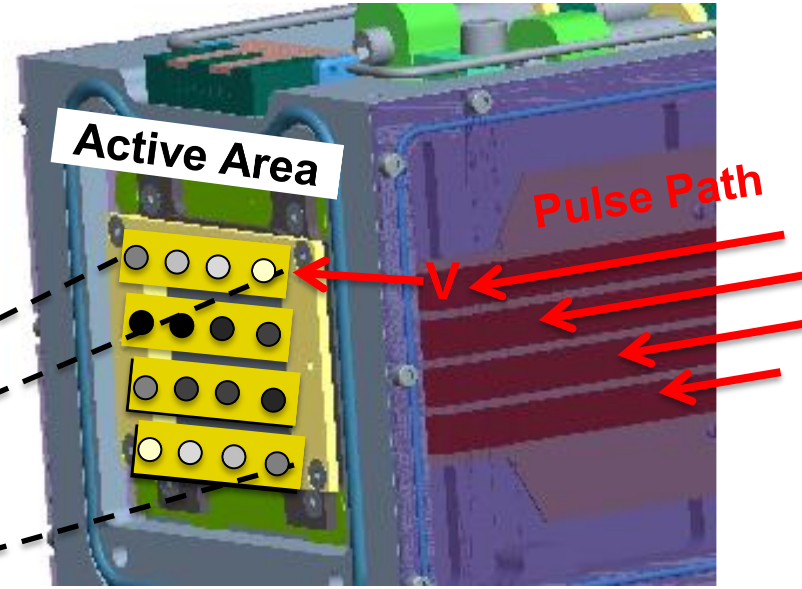
9 keV streaked radiograph



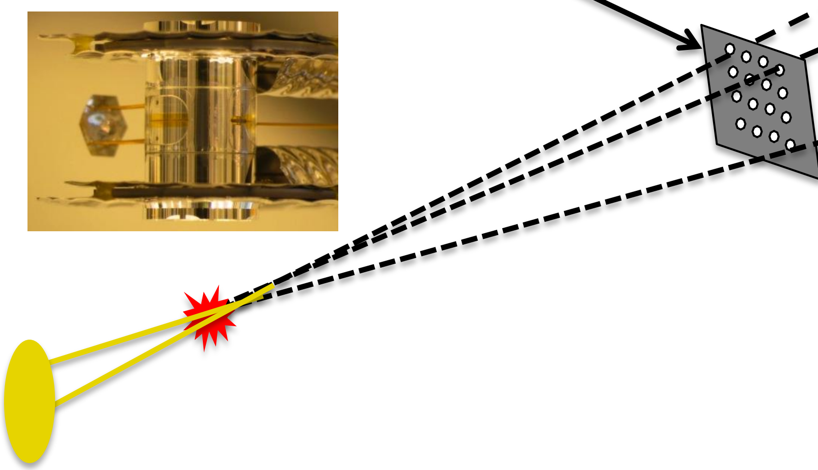
Continuous record of ablator r and δr

Gated(100 psec) x-ray detectors (GXD) are foundational- but have limitations



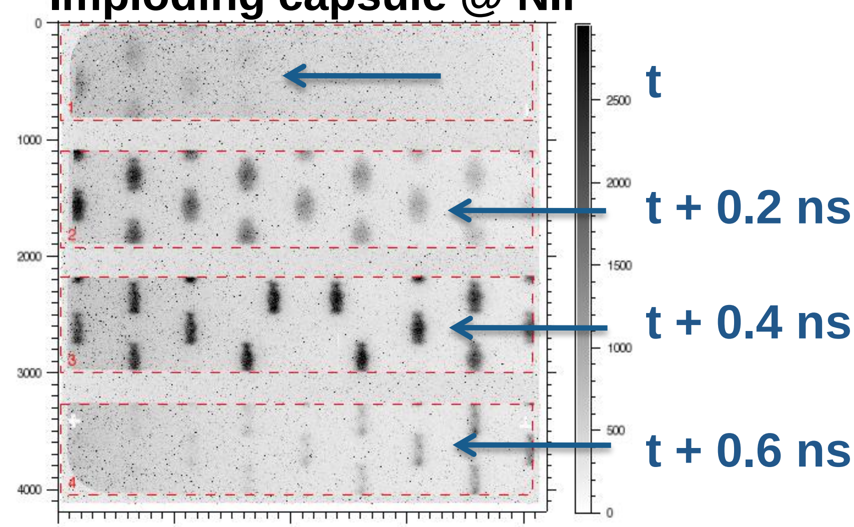


Array of pinholes produces many images, gated at different times- about f/10,000

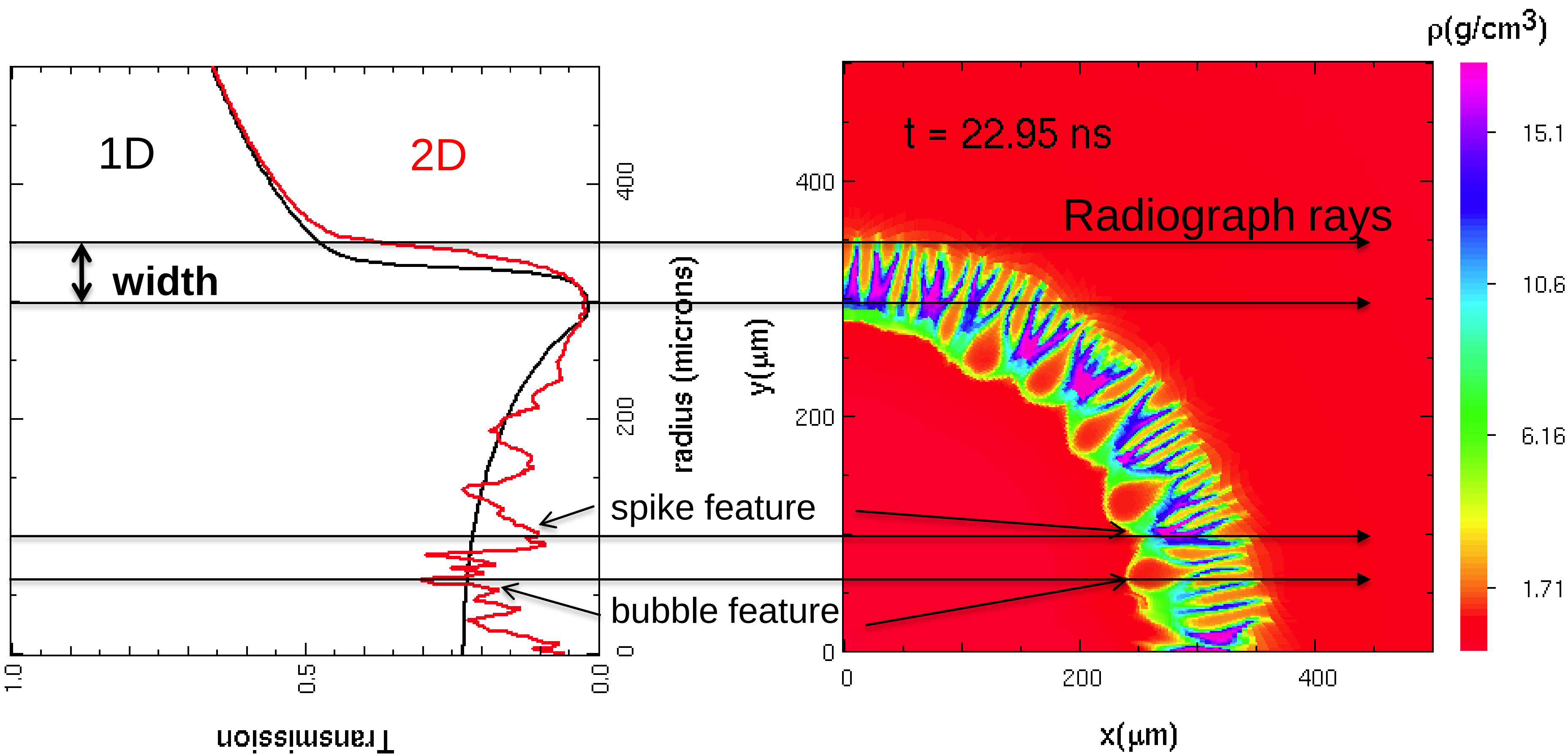


- Backlighter spot very close and large- needs 3X OMEGA energy to backlight

Imploding capsule @ NIF



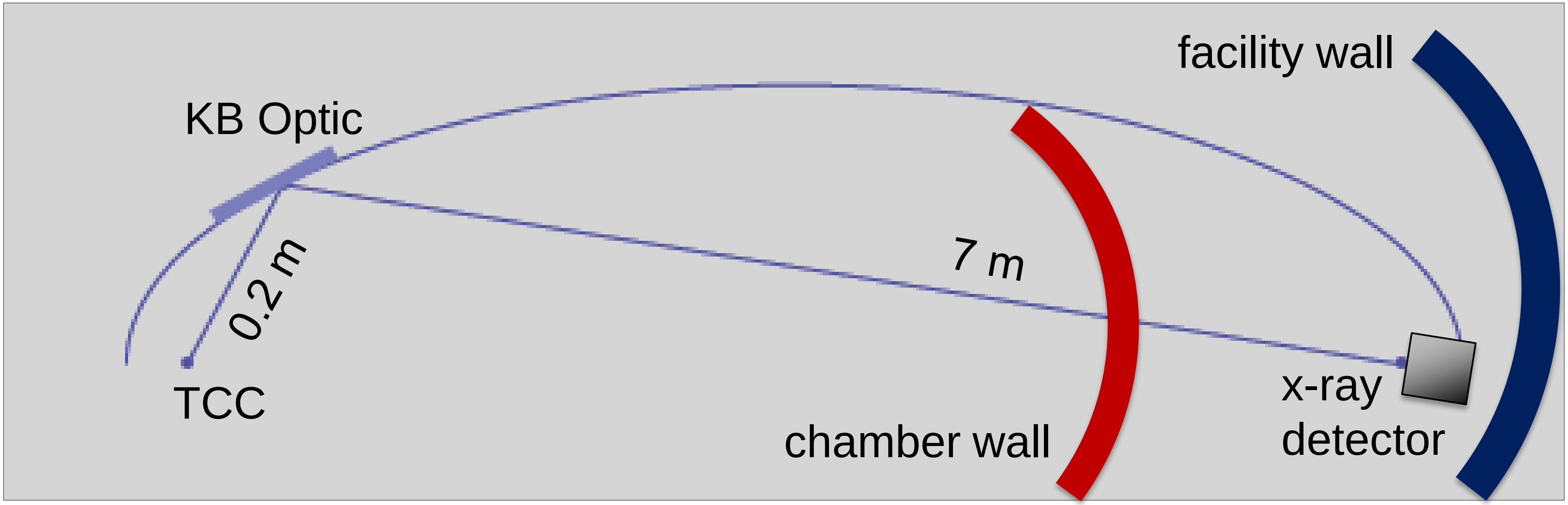
Gated backlit pinhole imaging might just see Rayleigh-Taylor bubble and spike features



Increasing x-ray collection with x-ray optic by ~X100 will make this easier

NIF's Chandra: – Single LOS gated x-ray microscope

- **Single Line of Sight framing**
- **Goal of 2 μm object resolution**
- **Magnification, M ≥ 30**



Diagnostics of the ablator and fuel implosion phase

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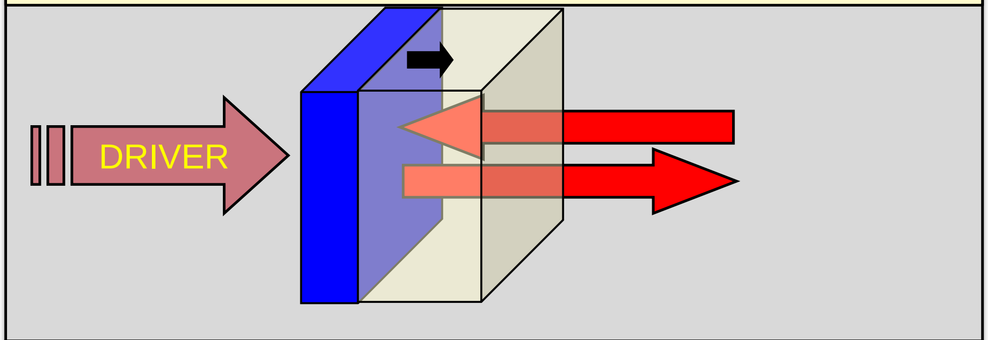
Interval	Bang time	X-ray flash	Gated imagers, SPBT	
		X_ray flash	SPIDER- streak	
		γ flash- Cerenkov	GRH, nTOF	
		Protons flash	Mag. pToF	

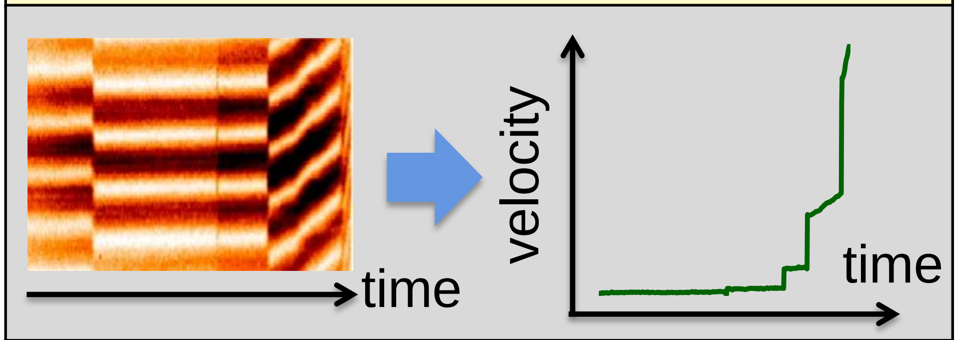
The VISAR is an optical probing diagnostic that detects Doppler shifts in a reflected probe beam

Probes shock fronts in transparent samples



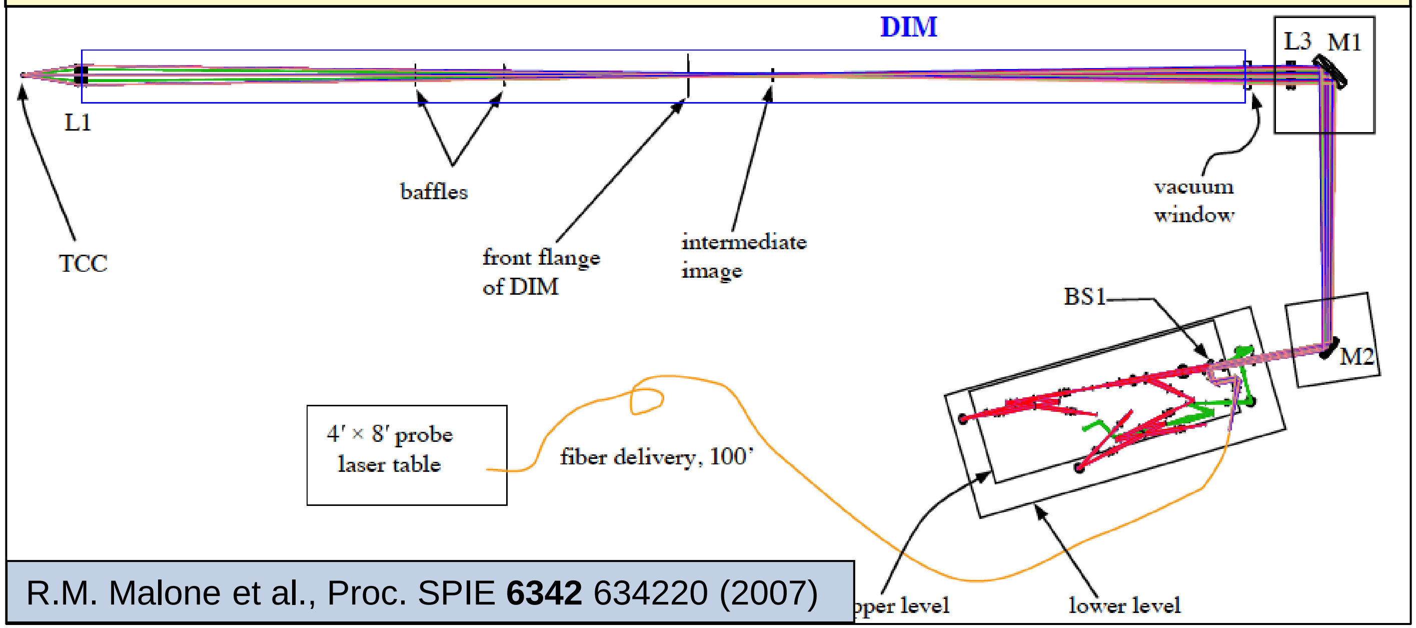
Reflection originates at shock front

VISAR: "Velocity Interferometer System for Any Reflector"



Doppler shift ⇔ fringe phase⇔ velocity

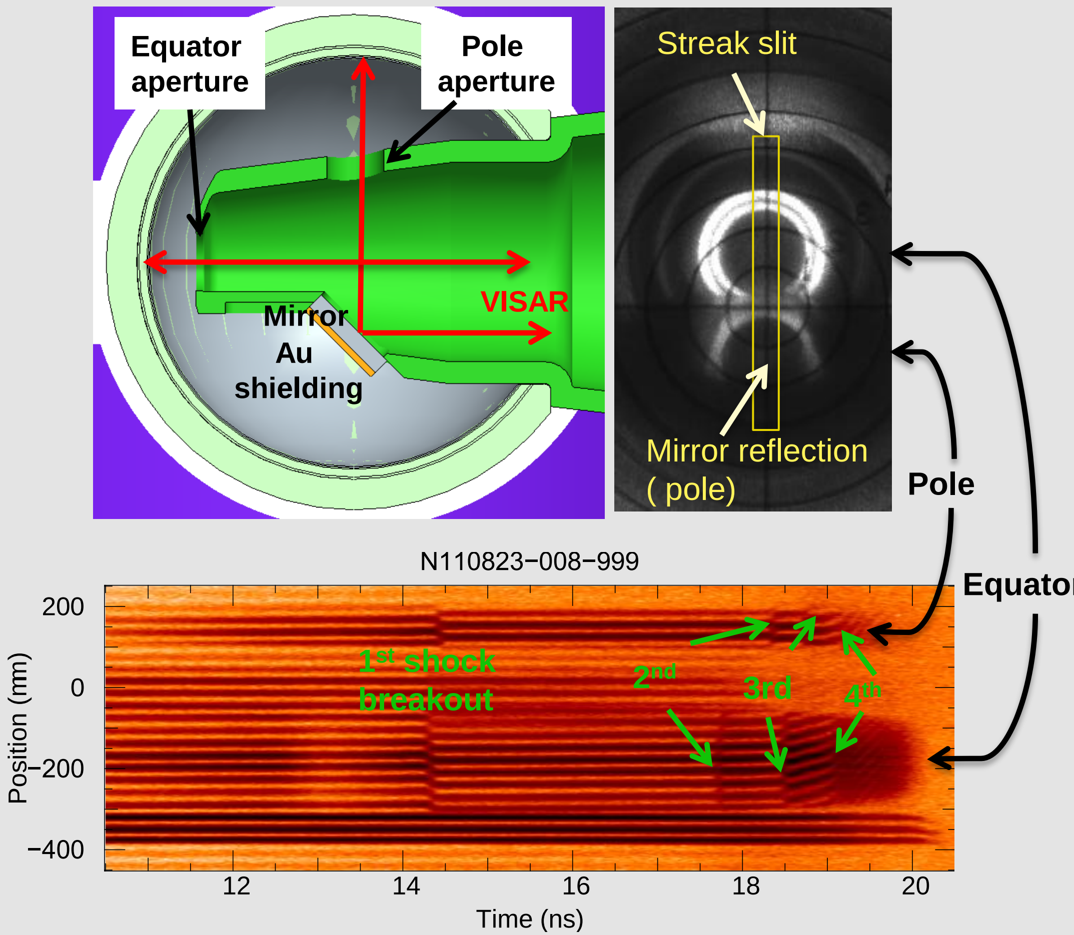
Reflection image projected onto streak camera



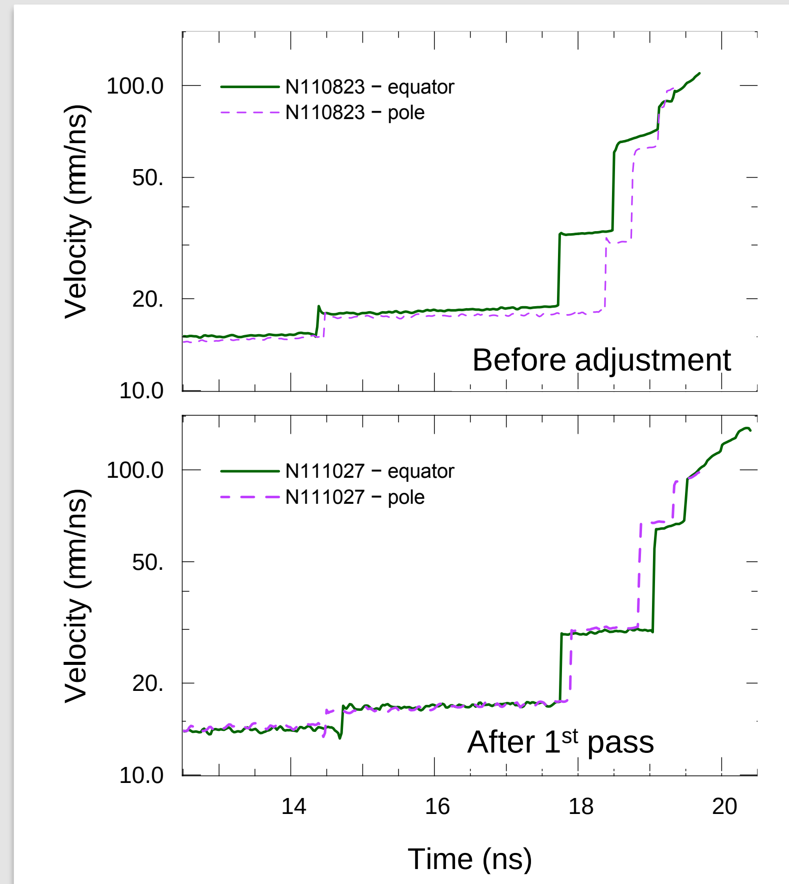
R.M. Malone et al., Proc. SPIE **6342** 634220 (2007)

mVISAR: dual simultaneous observation of the shocks on the pole and the equator

Target modified with a turning mirror incorporated into the cone



Pole and equator signals show differences in timing and velocity

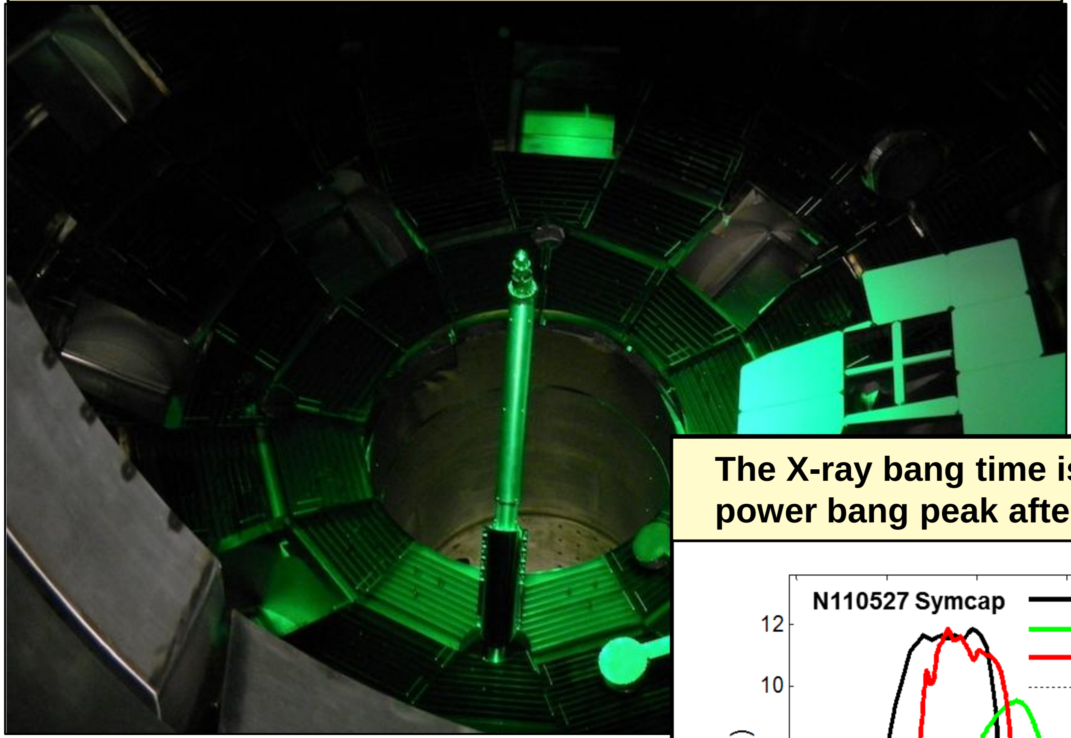


Feedback for cone fraction tuning

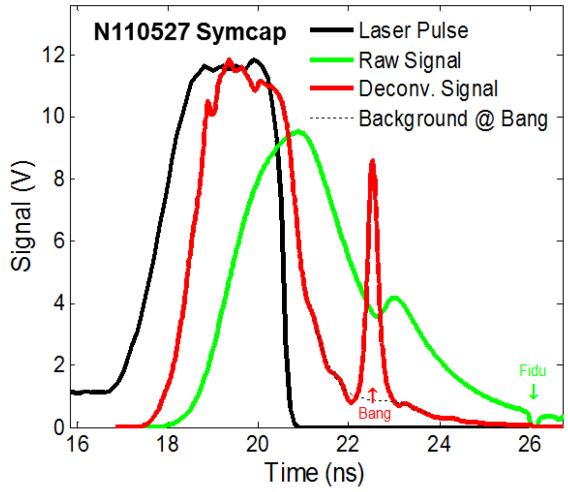
Has become the "standard" keyhole target platform

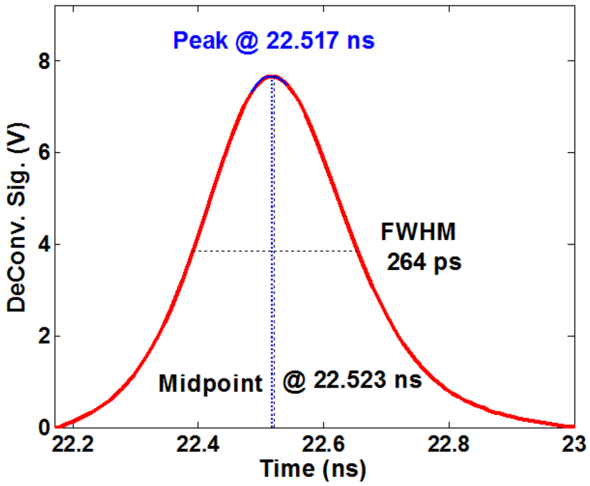
South pole bang time: X-ray detector routinely measures X-ray and neutron bang-time

South pole bang time detector looks up the hohlraum axis, sees implosion



The X-ray bang time is determined with an accuracy <50-ps from the X-ray power bang peak after the removal of the hohlraum background signal

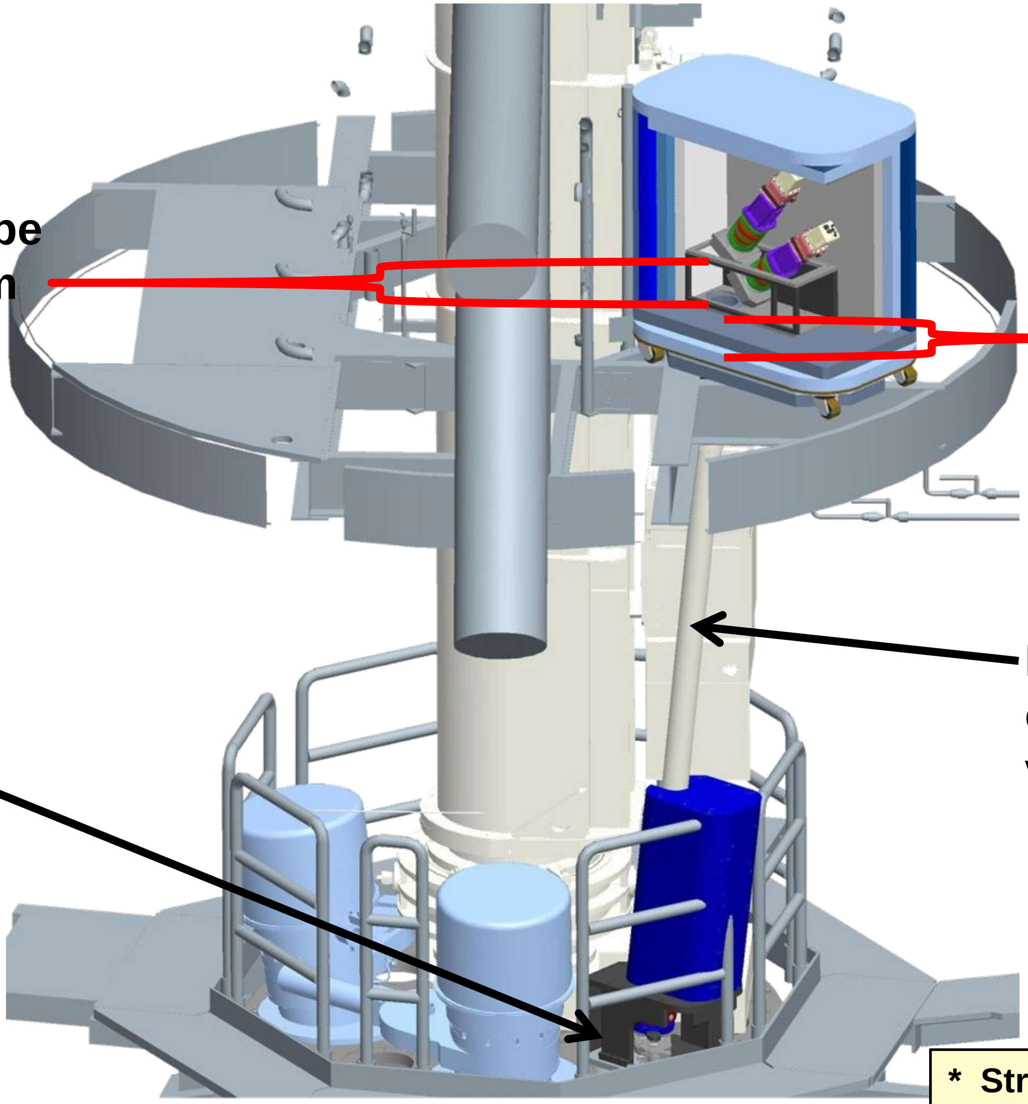




SPIDER* will measure X-ray bang time and emission history with 10 ps resolution up to ~10^{17}

Vacuum envelope is isolated from NIFs vacuum system

Air Gap



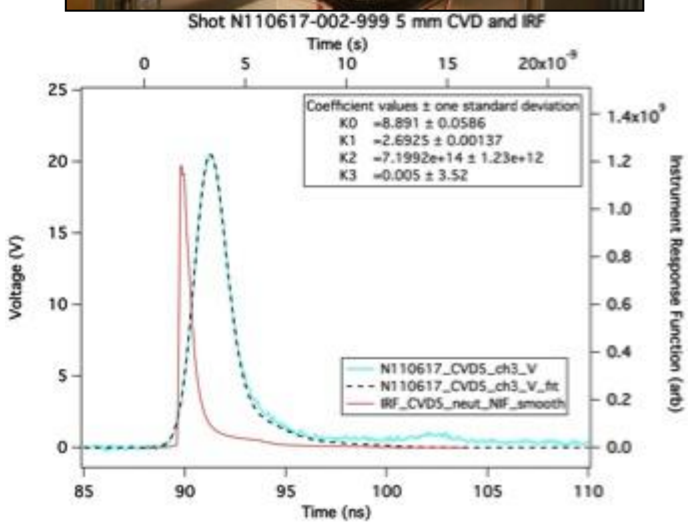
Diagnostic pipe connected to NIFs vacuum

Port D003B
$\phi = 90°$
$\theta = 7°$

* Streaked Polar Instrumentation for Diagnosing Energetic Radiation

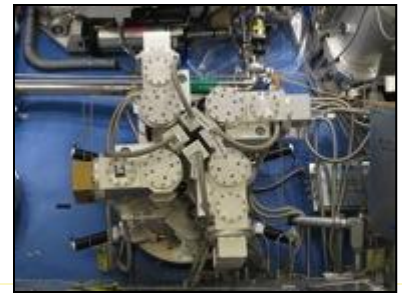
Two independents ways to measure neutron implosion bang time

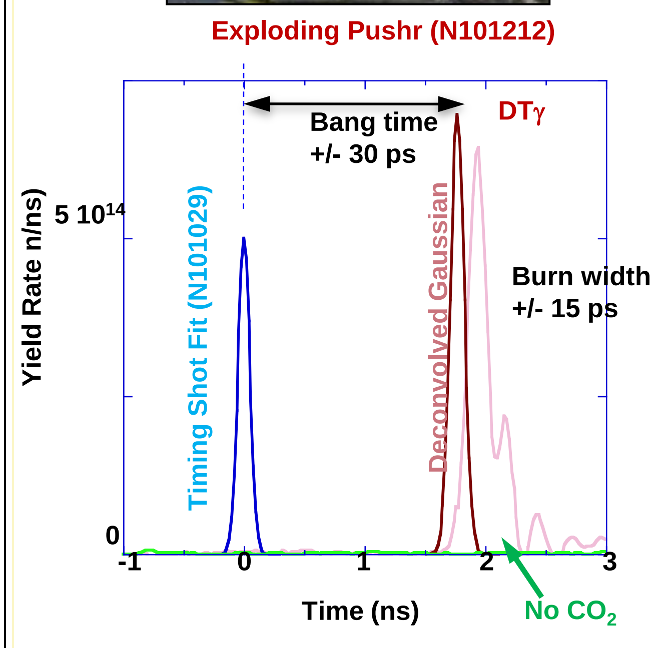
LLNL/LLE: Neutron time of flight (NTOF_BT)



Absolute accuracy to ±30 ps

LANL: Gamma Ray History (GRH)

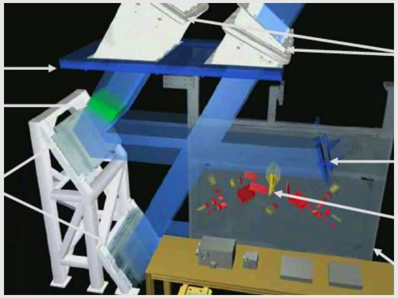




Absolute accuracy to ±50 ps

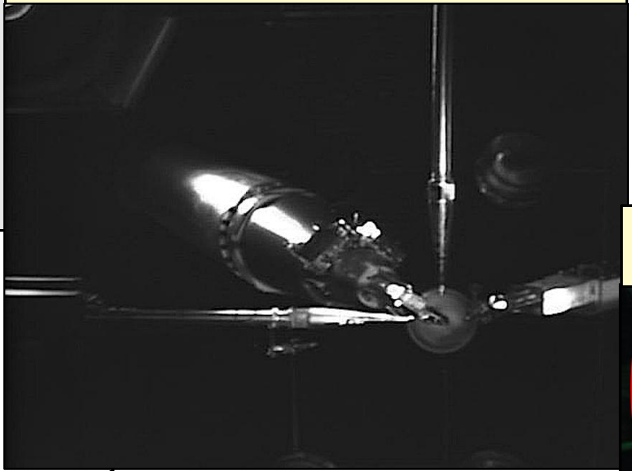
Road map

Hohlraum Energetics

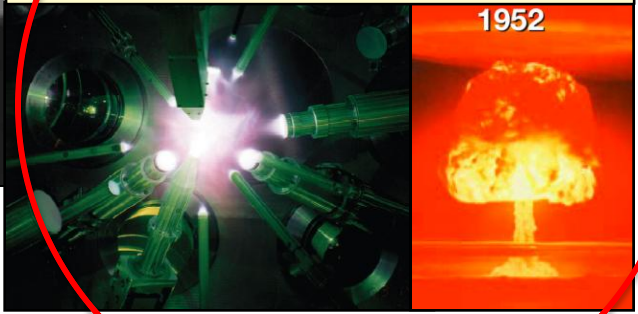


FABS31 on NIF

Implosion phase

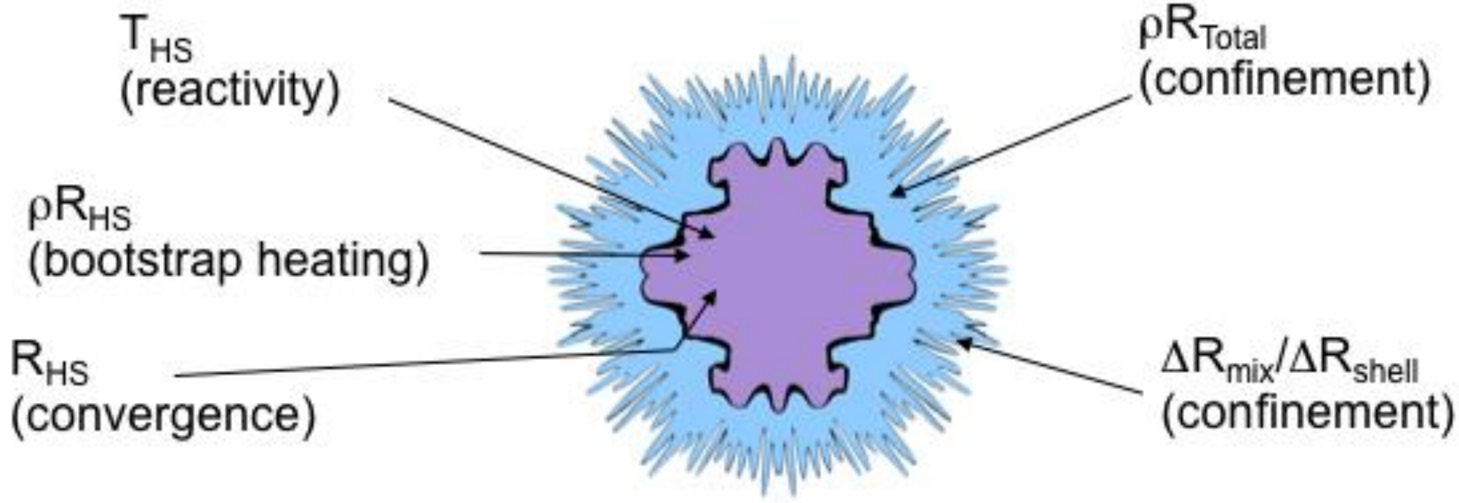


Assembly, burn phase



<u>How are we doing?</u>
-Good global measurements
-Starting to see microscopic features of shell and fuel during the implosion- improve xray backlighting

If the hot spot model is right this is what we have to measure

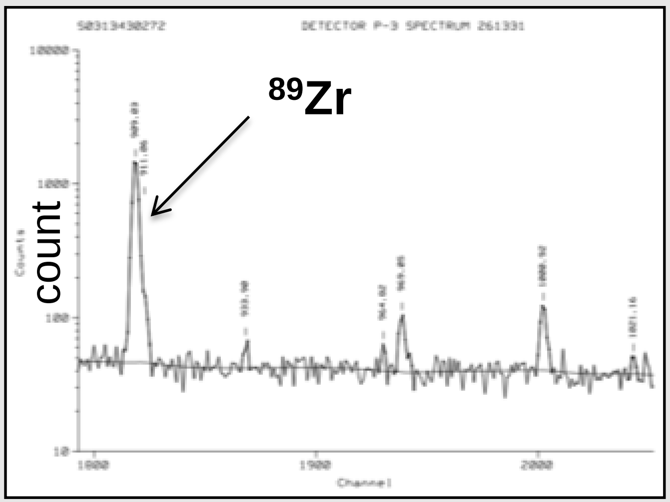


Assembly, stagnation and ignition diagnostics

	Attribute	Method	Acronym	Operational
Yield	Y_n , Y_p	activation, track det.	NADS, MRS,WRF	
Hot spot: r, dt	x-ray size: shape, dt	Pinhole imaging $<10^{16}$	hGXI, ARIANE	
	x-ray size: shape,dt	Imaging $< 10^{17}$	mARIANE	
	n size: shape	NI	NIS	
	n dt	Cerenkov	GRH	
Hot spot: T	T_e	Ross pairs imaging	GXD, hGXI	
	T_e(time)	gated	hGXI	
	T_{ion}	n Doppler	nToF, MRS	
	T_{ion}(time)	streaked n Doppler	tMRS	
	T_{ion}(time)	hi. Res. xray spect.		
Fuel	ρr- direction	n spectroscopy	nToF, MRS	
	ρr(θ,ϕ)	activation (θ, ϕ)	Flange NADS	
	ρr(θ,ϕ)	down sctt. n imaging	NIS	
	ρr	solid radchem	SRC	
	ρr	gas rad. chem	RAGS	
	ρr	low E n spectroscopy	LENS	
	ρr(θ,ϕ)	Compton radiography	CR	
	ρr(θ,ϕ)	ARC Compton	ARC-CR	
Mix	mix	dopant spectroscopy	Supersnout	
	mix	x-ray emission	Ross pairs	
	mix	solid radchem	SRC	
	mix	γ spectroscopy (C)	GRH	
	mix	γ spectroscopy (C)	NIF CGRO	

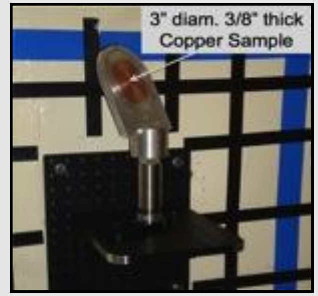
Yield is measured by three absolute and independent diagnostics and by three LABS

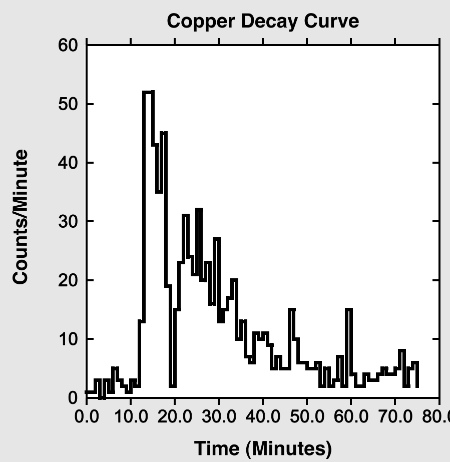
LLNL: Zirconium neutron activation (Well NAD)



Accuracy better than 7%* , activation cross section, detector efficiency

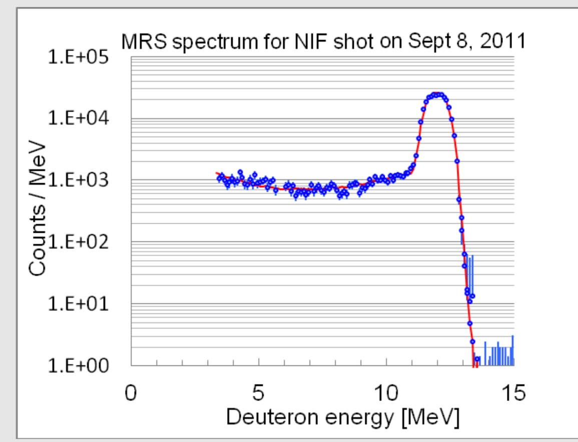
SNL:Copper neutron activation(NAD 20)





Accuracy better than 10%* , activation cross section, detector efficiency

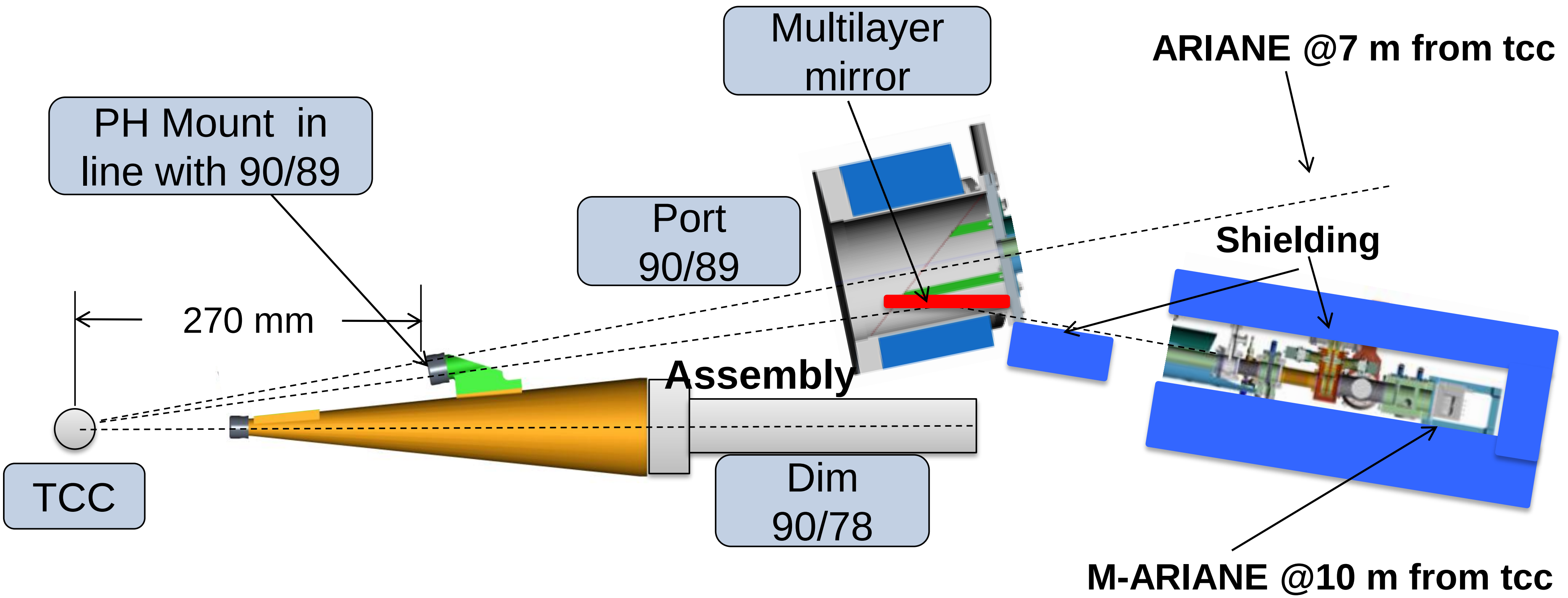
MIT: Magnetic Recoil Spectrometer (MRS)



Accuracy 5%* , n-d cross section, diagnostic geometry

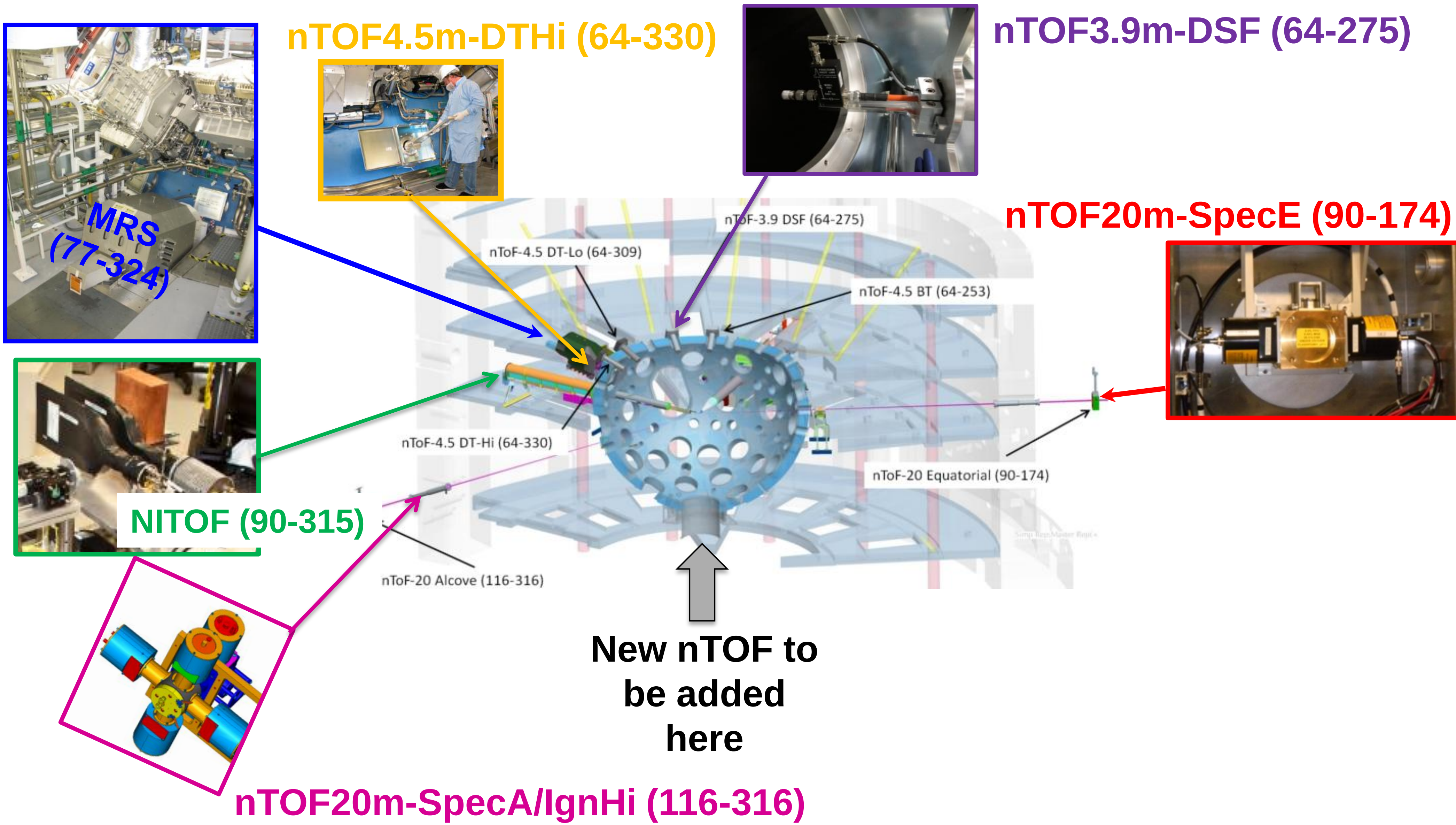
Assembly

X-ray imaging with yield requires moving the shielded detector out of the line of sight with an x-ray mirror M-ARIANE

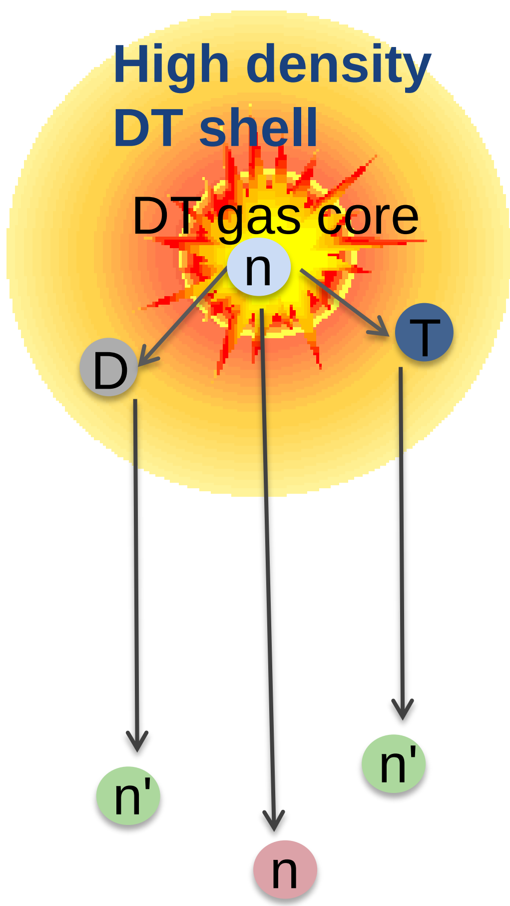


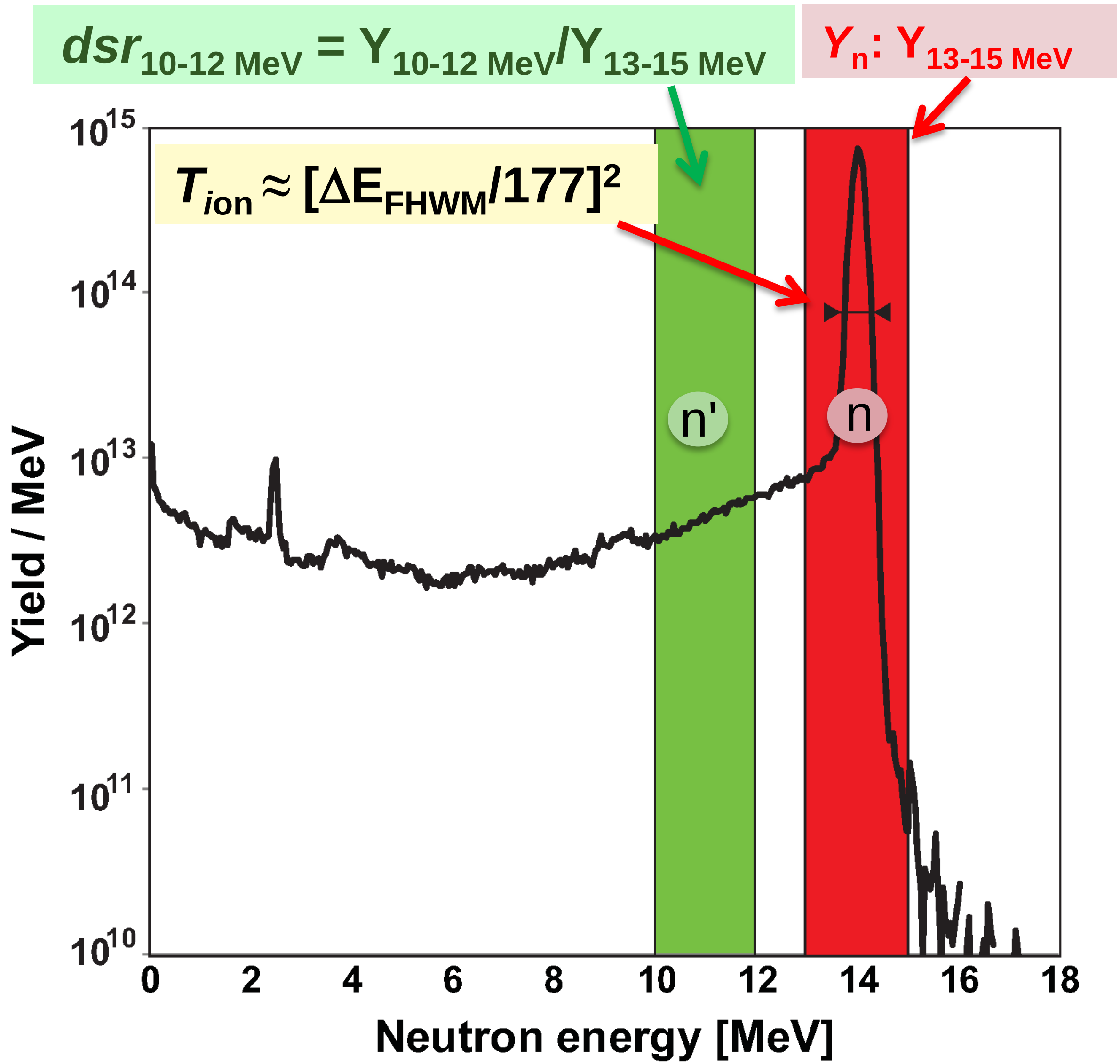
M-ARIANE can use film or dump-and-read electronic readout for image recording

A suite of neutron spectrometers fielded at various locations are used to measure the directional neutron spectrum



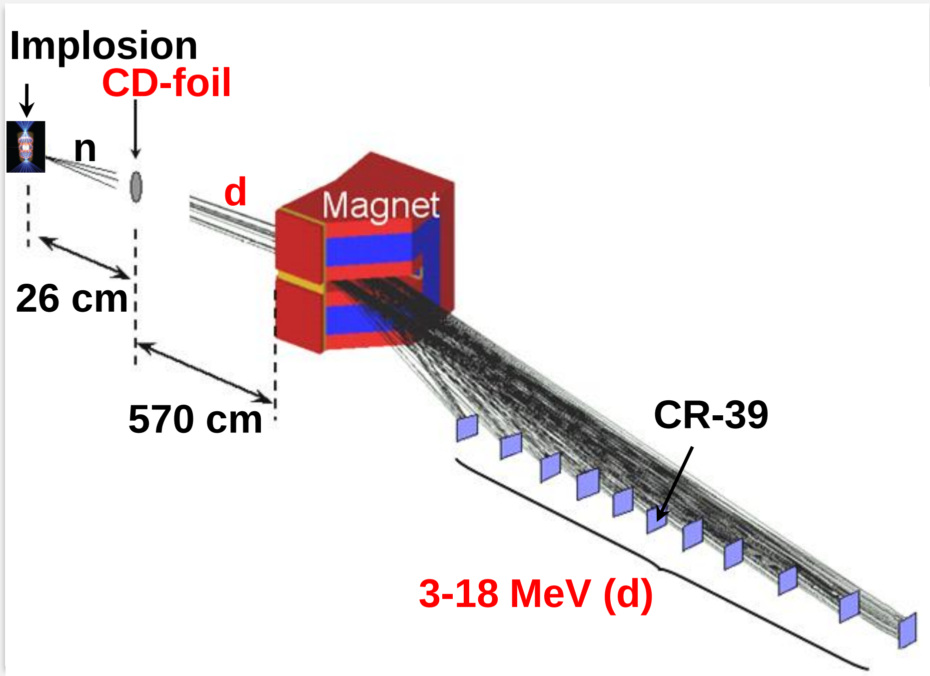
The ICF-neutron spectrum provides information on ρR, T_i and Y_n - Essential info for assessing implosion performance





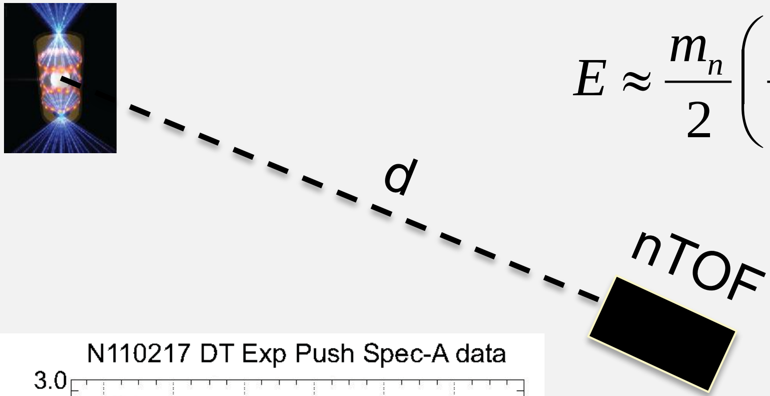
The existing neutron spectrometers are based on two different concepts

Magnetic Recoil Spectrometer (MRS)

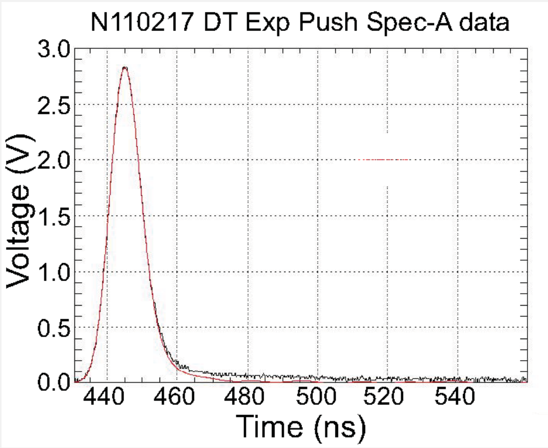


The neutron spectrum is inferred from the measured recoil deuteron spectrum

neutron Time of Flight (nTOF)

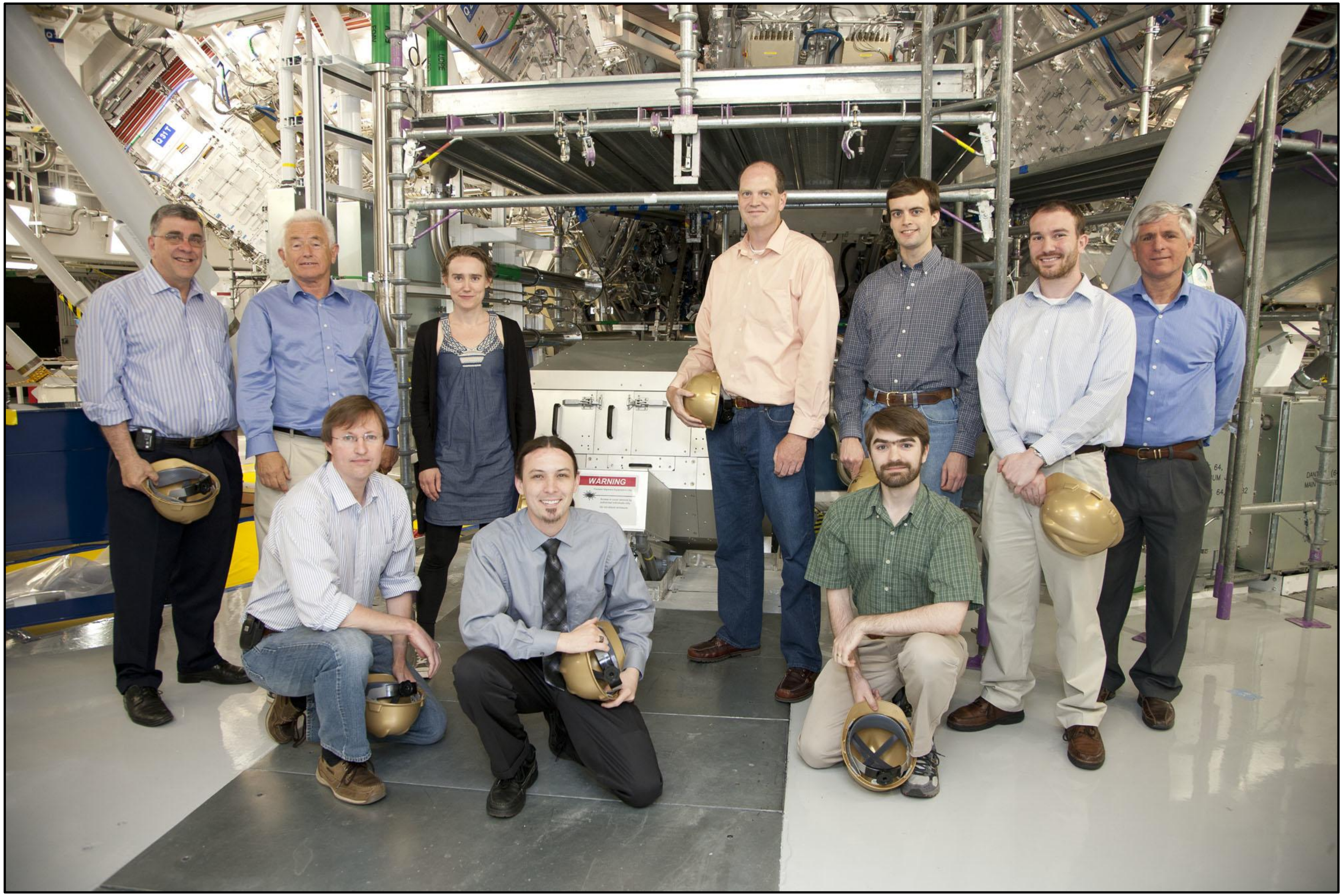


$$E \approx \frac{m_n}{2}\left(\frac{d}{t}\right)^2$$



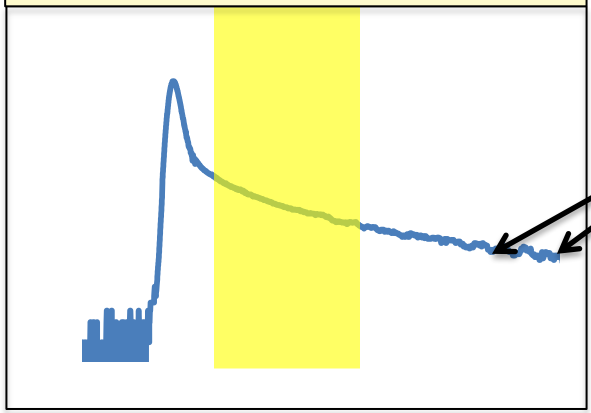
The neutron spectrum is inferred from the time-dispersed signal

MRS has been a great University alliance success

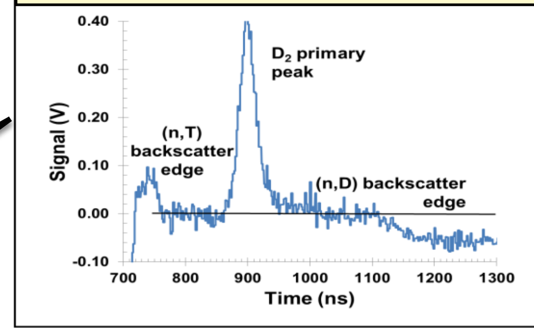


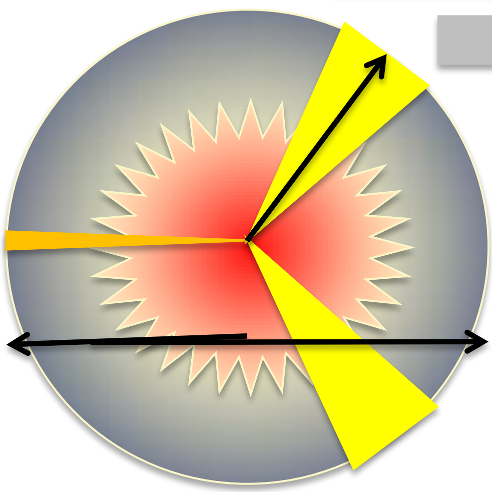
“(R)evolutionary improvement of NToF: back scattered & down scattered neutrons probe different cold fuel regions

NToF - logarithmic



The (n,T) and (n,D) backscatter edges are clearly visible in the nTOF 20-SpecE spectrum once the yield from other neutron producing reactions is removed





neutrons

nT and nD down scatter 10 – 12 MeV

neutrons

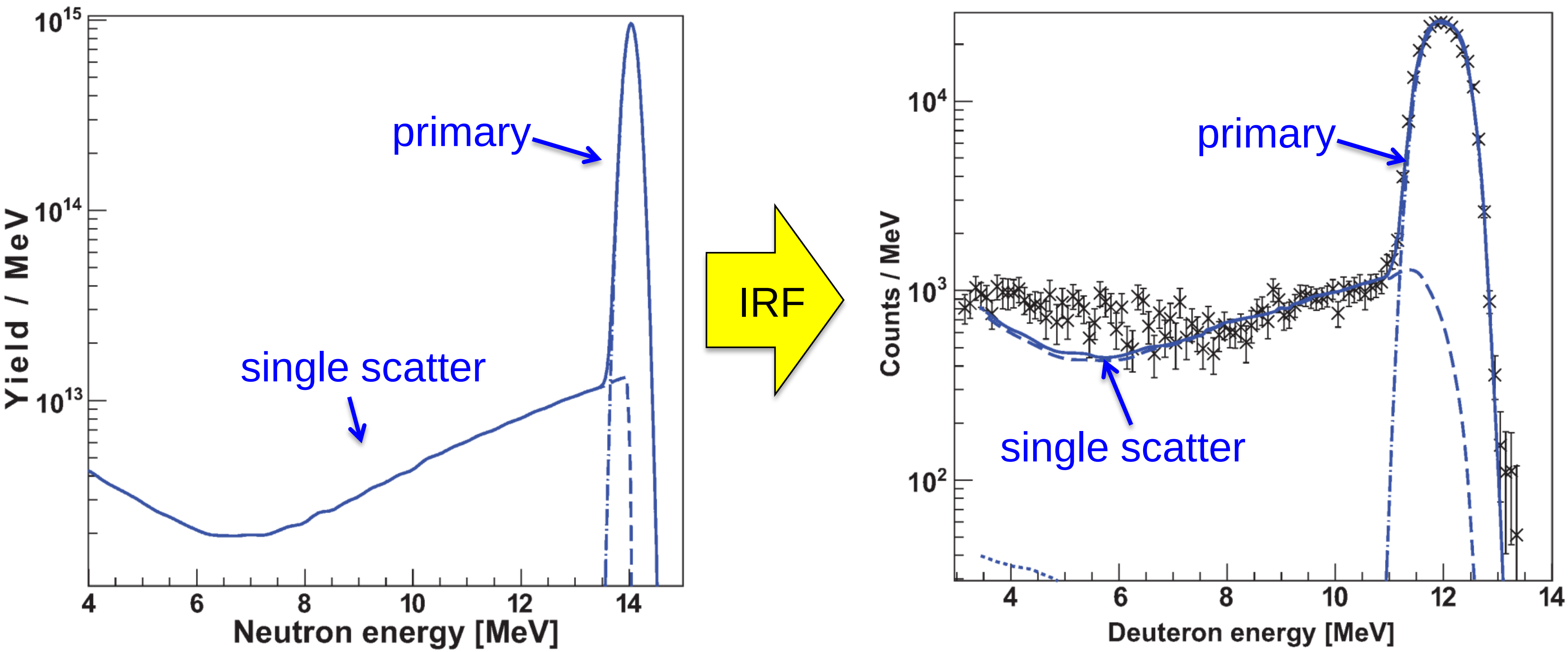
DT neutrons from Hot Spot 14 MeV
D_2 neutrons from Hot Spot 2.45 MeV

neutrons

nT back scatter 3.5 MeV
nD back scatter 1.6 MeV

A single scattering model cannot explain the low-energy neutron spectrum in high-ρR implosions

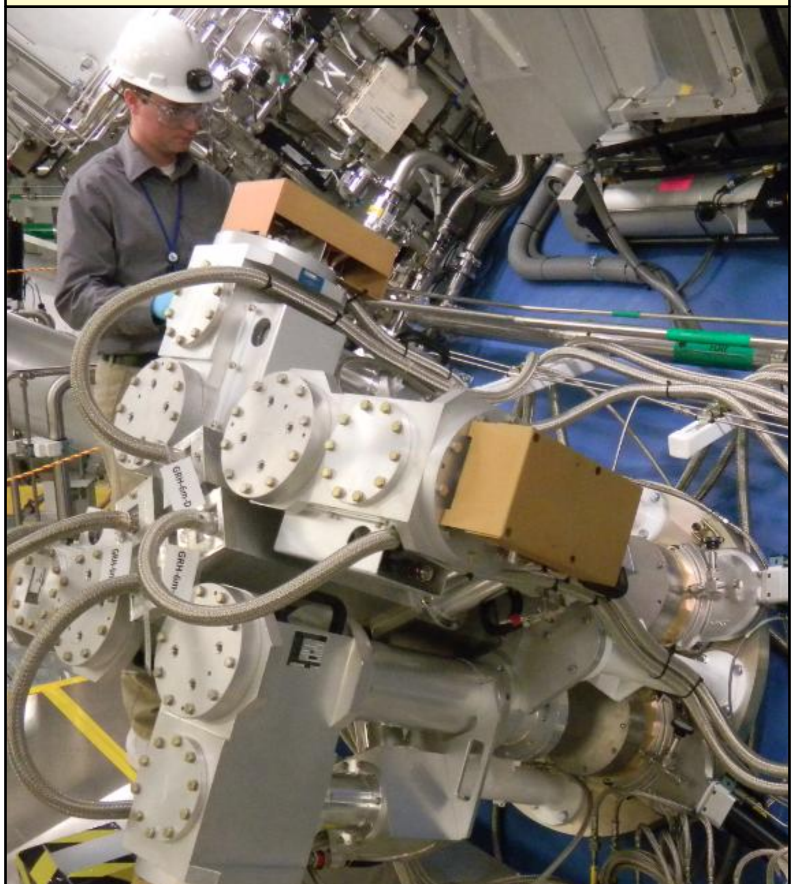
MRS data for Cryo DT, Nov. 12, 2011



ρR asymmetries and multiple scattering may be important at energies below ~9 MeV, and will be considered

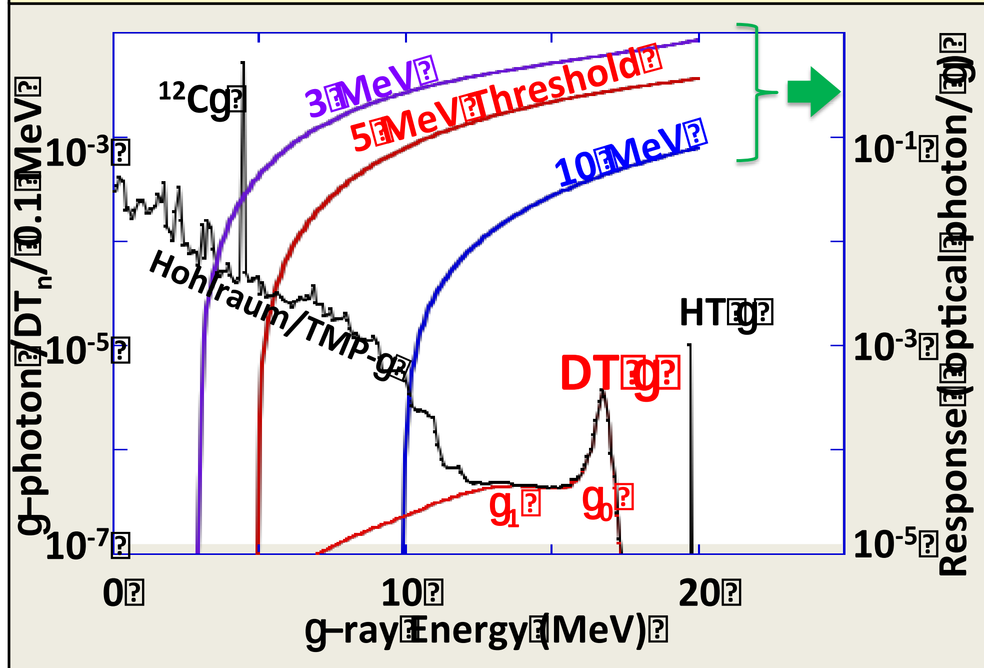
The GRH is the first generation gamma-ray spectrometer

GRH installed at NIF



4 Gas Cells mounted on chamber (6 m from TCC)

Predicted Gamma-Ray Spectrum

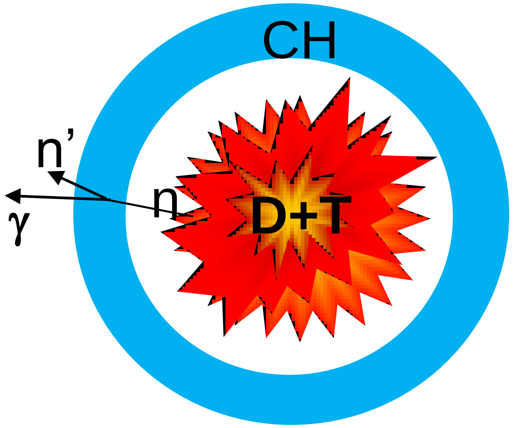


Energy thresholded measurements to provide:

- — Total DT yield
- — Plastic Ablator Areal Density

Areal Density of imploding plastic capsule can be inferred from gamma-ray yields

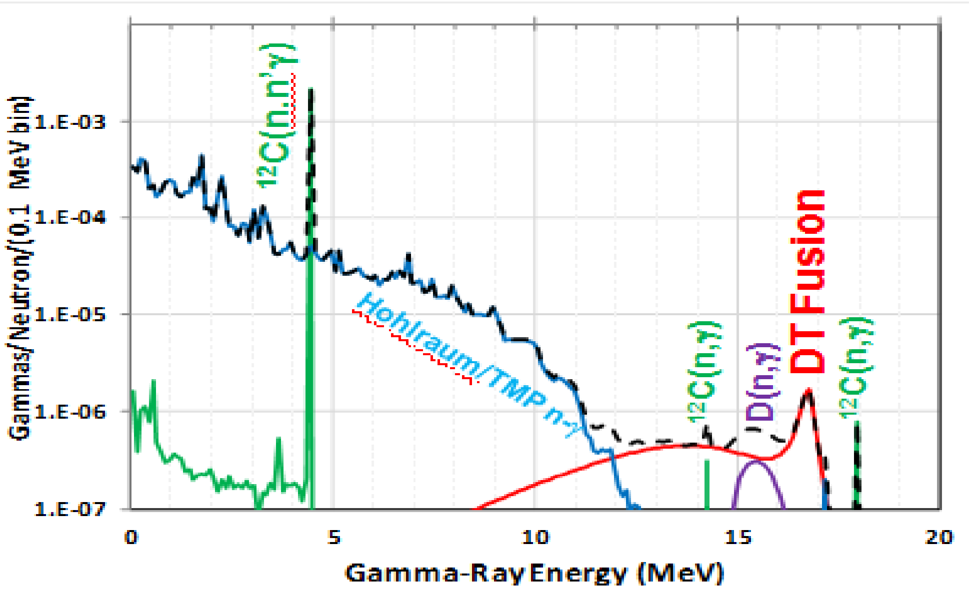
- 14 MeV neutrons inelastically scatter off ^{12}C in plastic ablator producing $^{12}C(n,n')$ 4.44 MeV γ-rays
- GRH unfolds 4.44 MeV signal providing a measure of ^{12}C ρR



$$Y_{\gamma C} \cong \frac{\sigma_{^{12}C(n,n')}}{m_C} < \rho_C R > Y_{nDT}$$

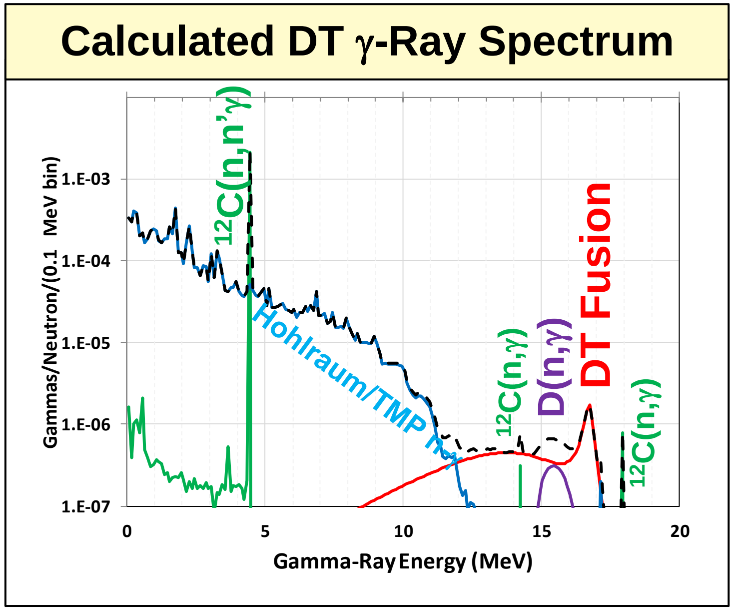
$$Y_{nDT} = Y_{\gamma DT} / B \approx Y_{nDT(12-15MeV)}(1+3DSR)$$

$$< \rho_C R > \cong \frac{m_C}{\sigma_{nC}} \frac{Y_{\gamma C}}{Y_{nDT}}$$



- ^{12}C ρR depends on:
  1) Ablator Mass Remaining
  2) Ablator Compression
  3) Ablator Mix into Hot Spot

Future Gamma Spectroscopy could provide valuable information to a large range of neutron rich implosions



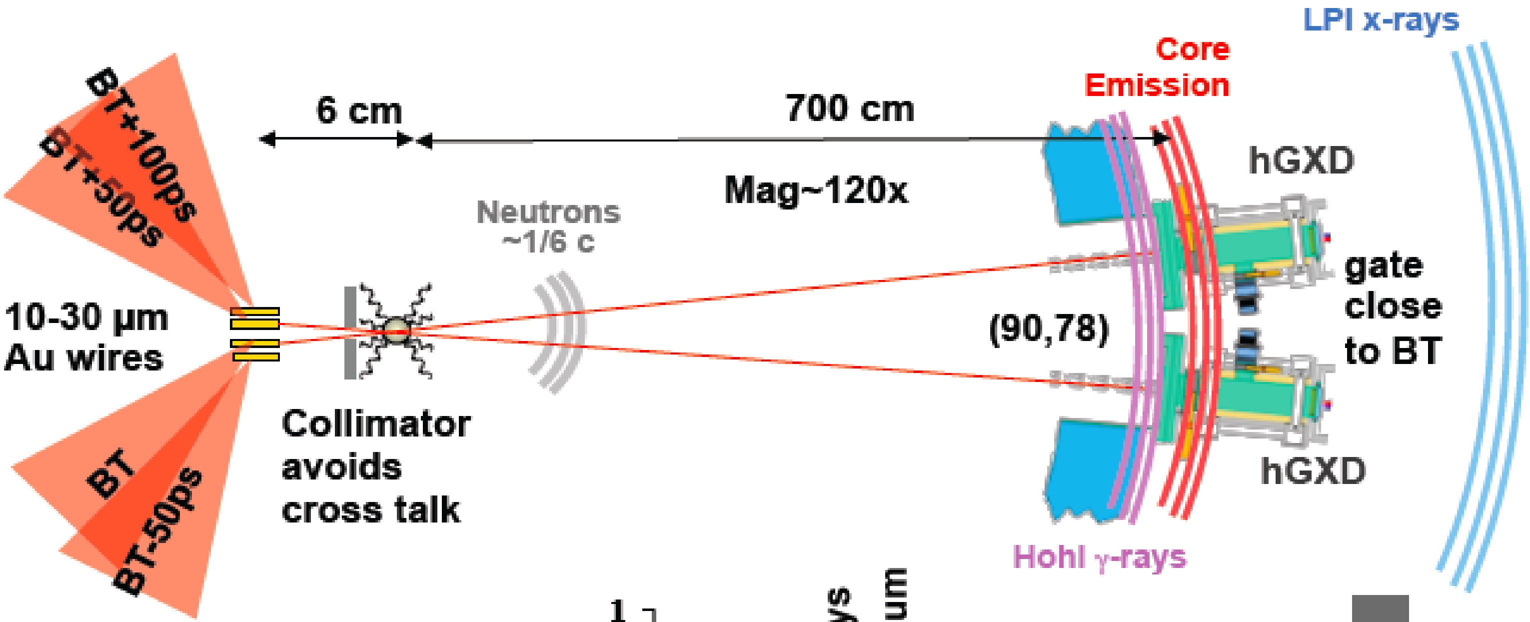
Reaction	Application	Energy (MeV)	Requirement (for 100 γ detection)
DT Fusion	Total DT Yield	16.75, 13.5	Y>1e15 for γ_0; Y>3e15 for γ_1
D(n,γ)	Fuel ρR	15.58	Y>3e15 for ρR_{fuel} >1 g/cm^2
^{12}C(n,n'γ)	CH Ablator ρR	4.44	Y>3e14 for ρR_{CH} >200 mg/cm^2
^{16}O(n,n'γ)	Be Ablator ρR	6.1, 6.9, 7.1	Y>1e15 for ρR_{Be} >200 mg/cm^2
^{13}C(d,n)^{14}N*	CH Mix	5.69, 8.06	Y>3e16 w/Mix (but w/in TMP n-γ)
^{9}Be(α,n)^{12}C*	Be Mix	4.44	
^{9}Be(d,n)^{10}B*	Be Mix	3.4, 4.49, 6.03	

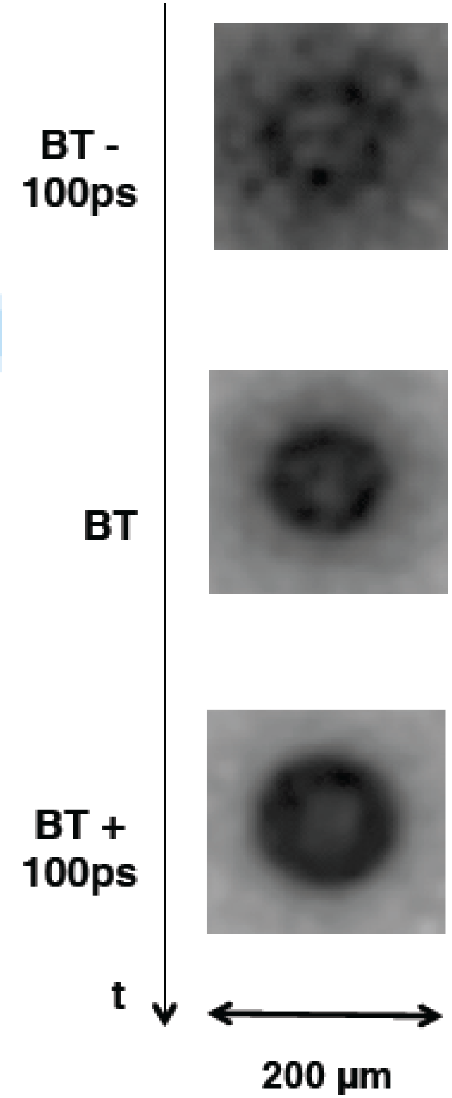
How to measure where the compressed fuel is?

- Compton Radiography with existing NIF
- Compton Radiography with ARC
- Anisotropy of un-scattered primary neutrons
- Down-scattered neutron imaging

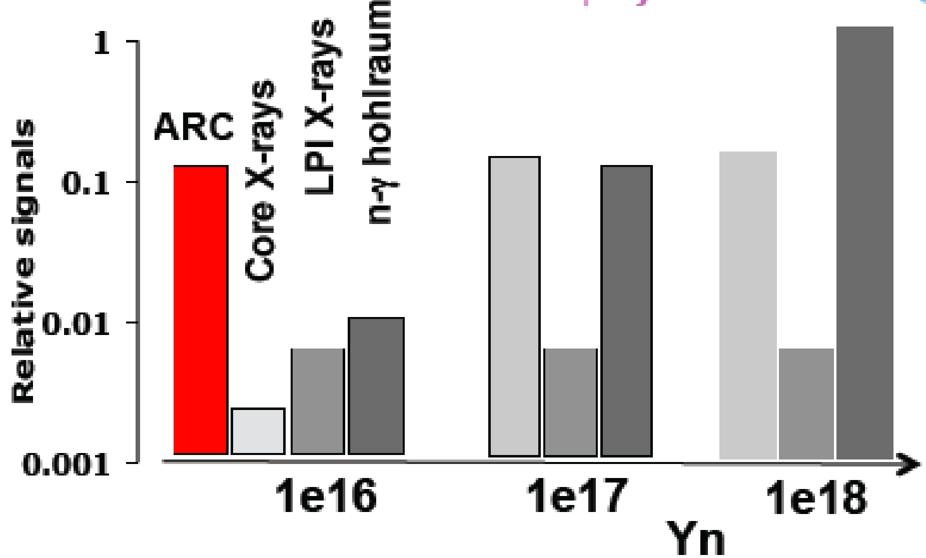
ARC + distant shielded gated detectors will extend Compton Radiography to 1e14–1e17 yield regime

ARC requirement: > 800 J @ < 30 ps, > 1e17 W/cm² per subaperture beam



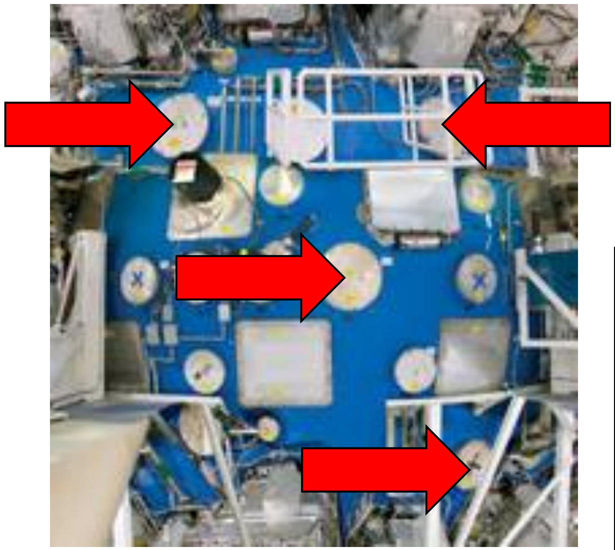


Predicted signal and background levels

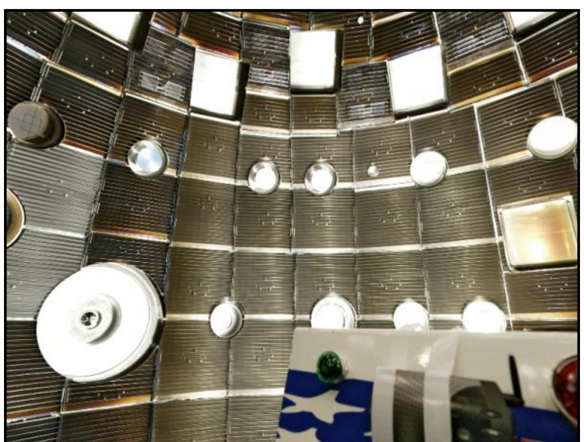


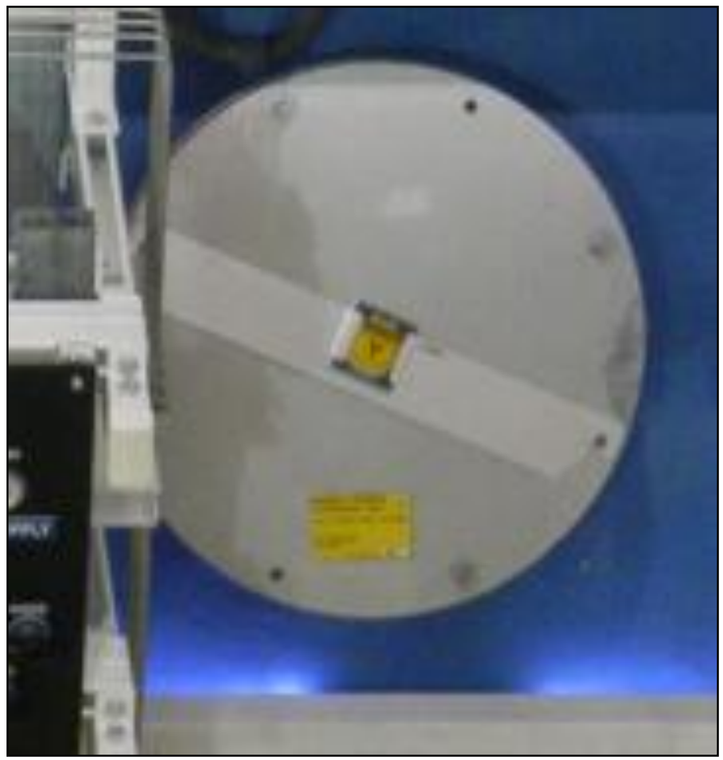
A set of Neutron Activation Detectors (NADS) measures anisotropy in un-scattered neutrons to ~ 3%

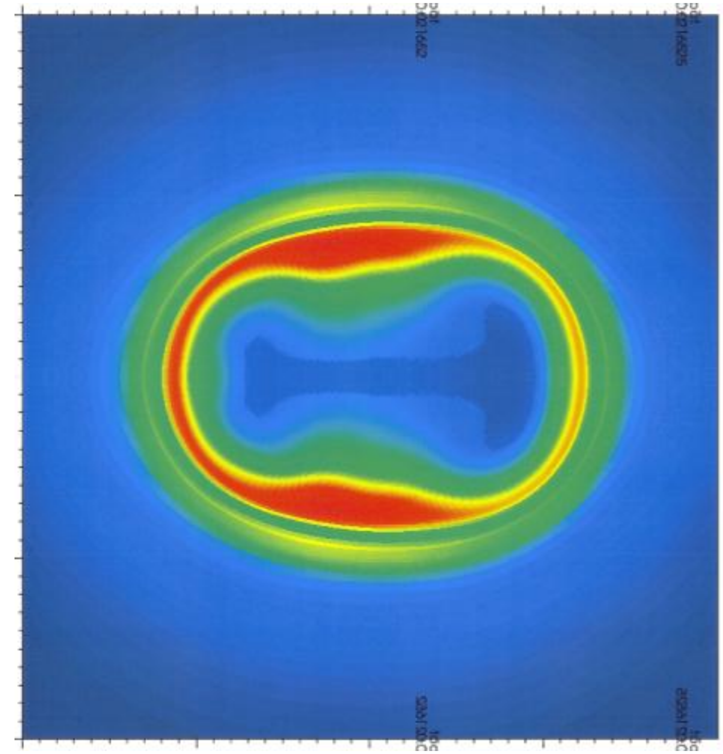
Zirconium samples mounted outside 9-16 ports around target chamber

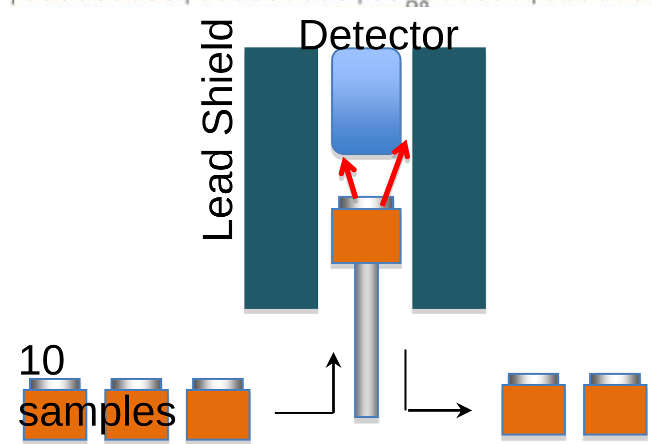


(not actual locations)

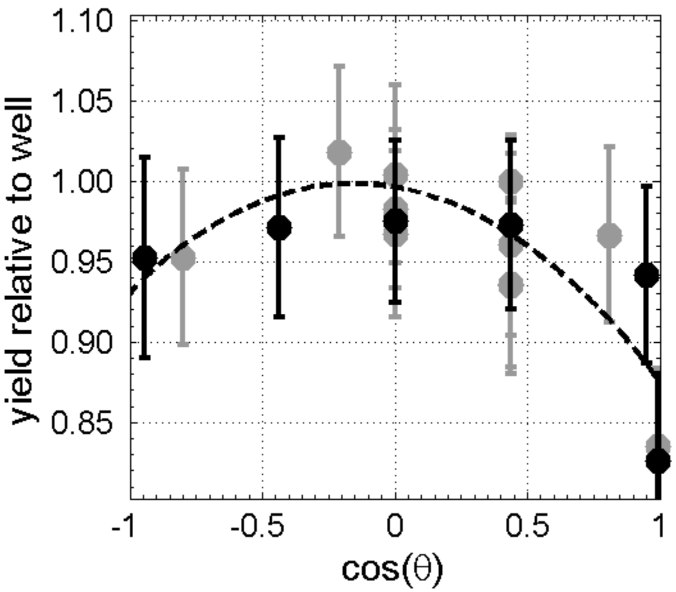


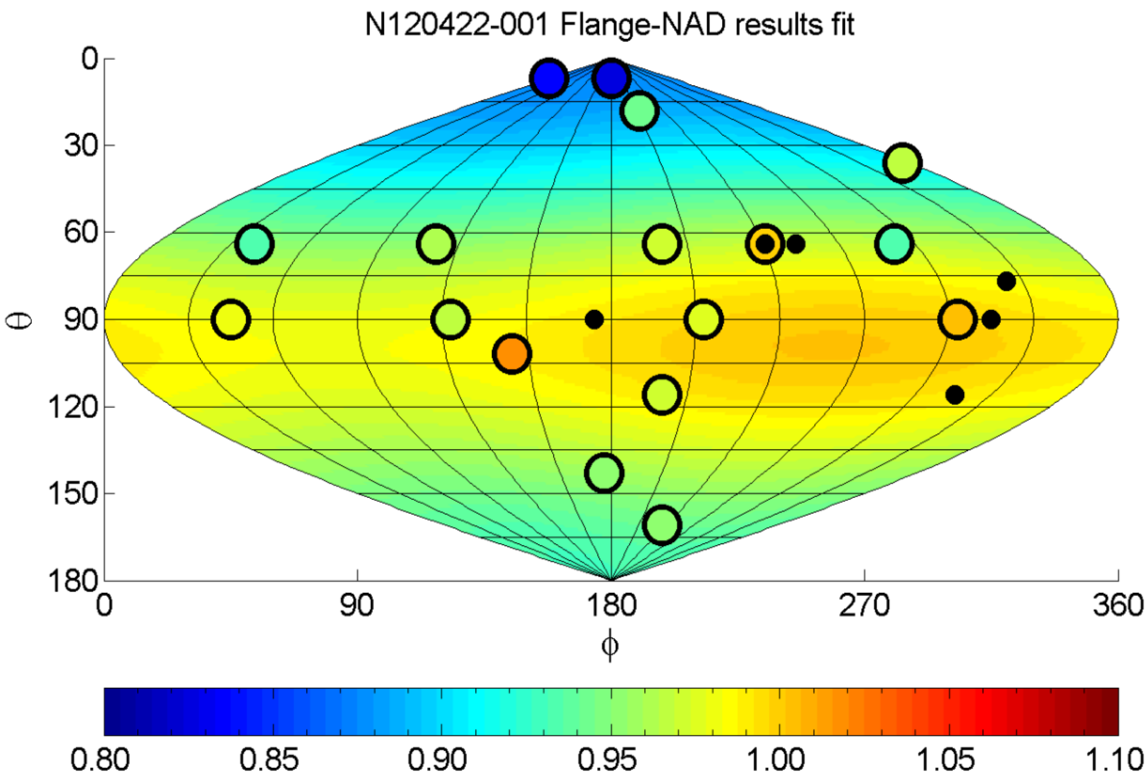






Measuring activation in many directions hints at more fuel at the poles of the imploded core

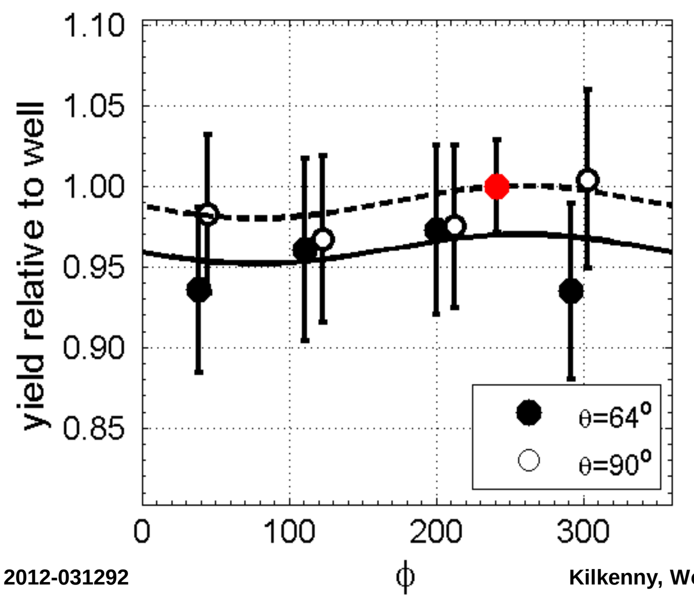




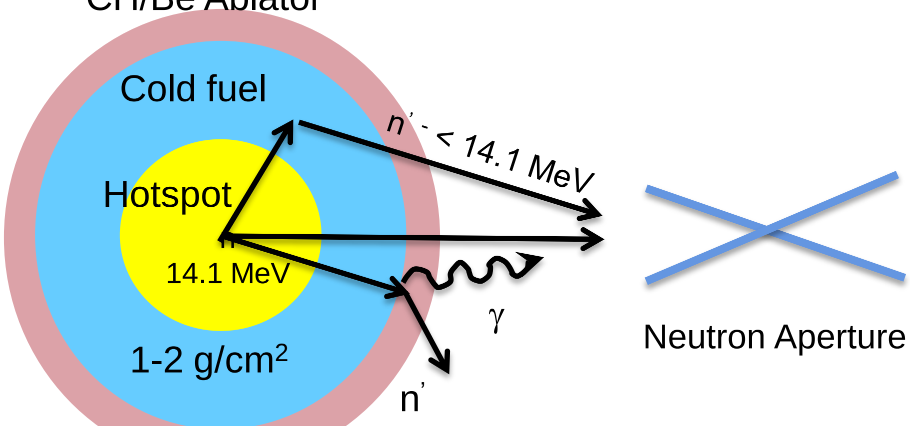
as=3.406
apz=-0.057
apx=-0.004168
apy=-0.02027
adz^2=-0.1849

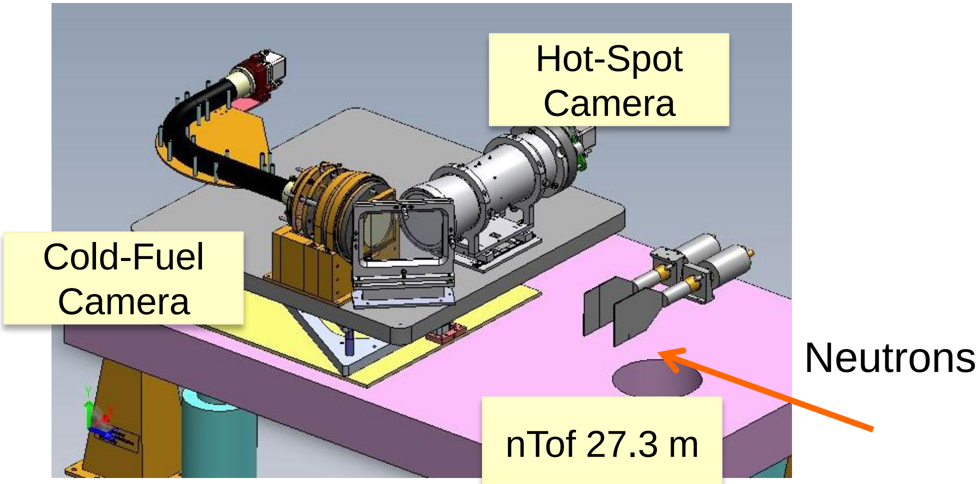
Well-NAD: 0.96965
MRS: 0.98337
nToF BT: 0.97003
SpecA: 0.99027
specE: 0.99099
NI(90-315): 0.99556

|Y1m|: 0.060643 +- 0.041412
adjR^2=0.522

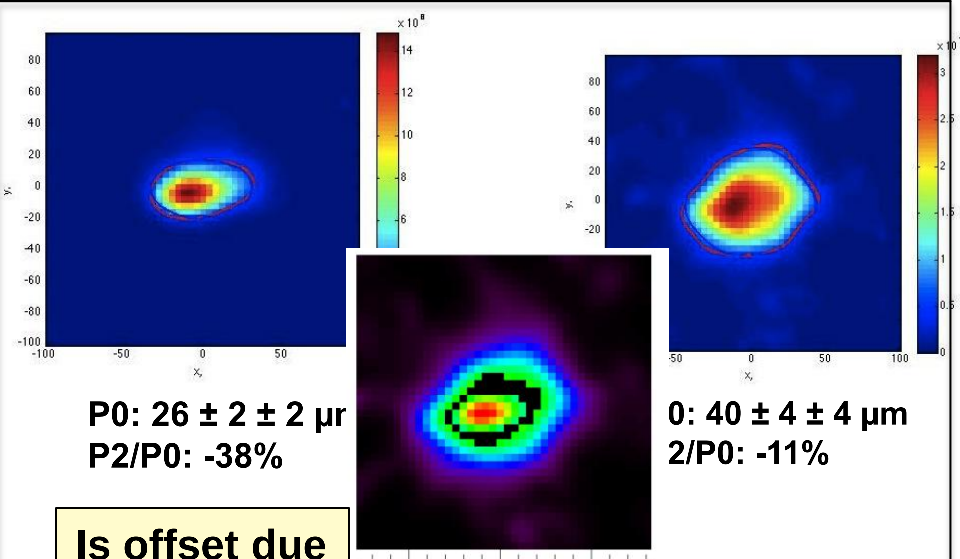


Neutron imaging provides spatial information on neutron production and scattering





Co-registration of primary and down-scatter neutron image shows where the fuel is



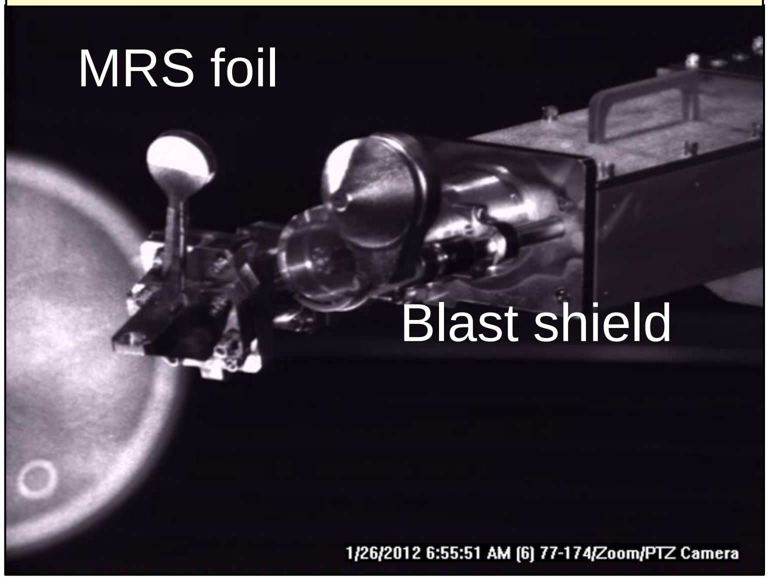
P0: 26 ± 2 ± 2 μr
P2/P0: -38%

0: 40 ± 4 ± 4 μm
2/P0: -11%

Is offset due to fill tube?

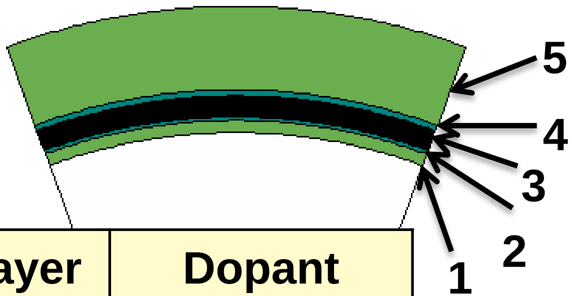
3-17 MeV , > 50%
10-12 MeV , < 60%

Neutron pin-hole during alignment

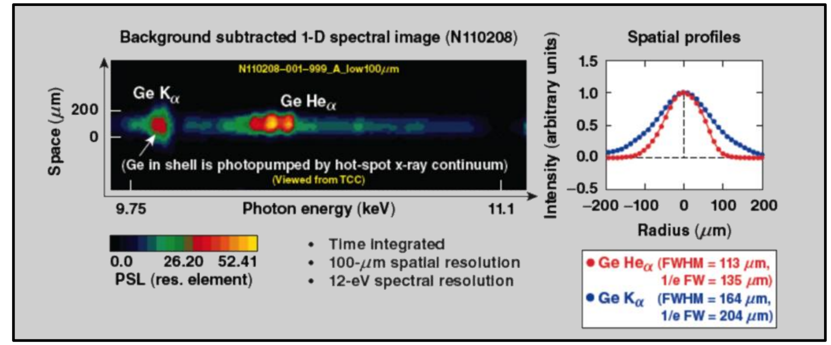


Doped capsules and spectrometer have been designed to trace origin of ablator mix in the hot spot

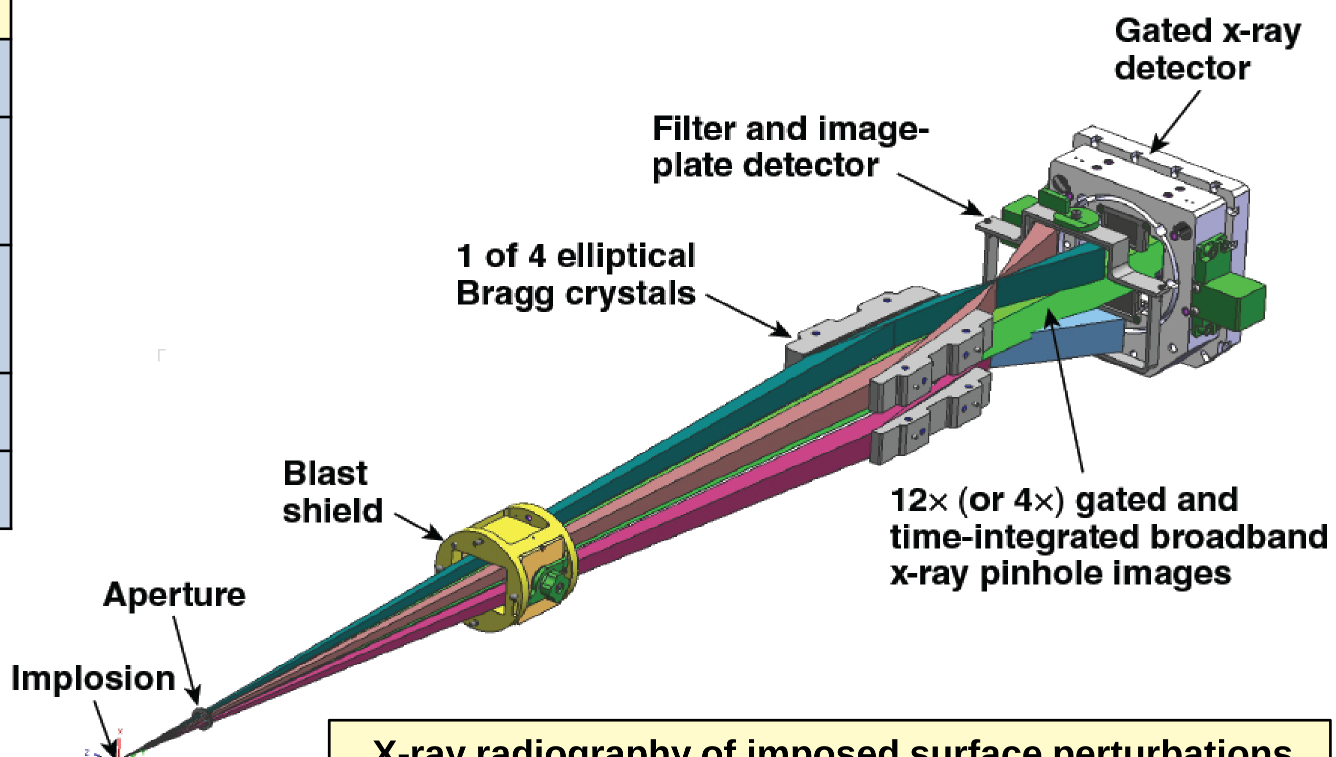
Cu, Ge, Si doped CH ablator



Layer	Dopant (atomic %)
1	Cu(0.1%)
2	Si(0.7%) Ge(0.15%)
3	Si(1.7%) Ge(0.15%)
4	Si(1%)
5	none



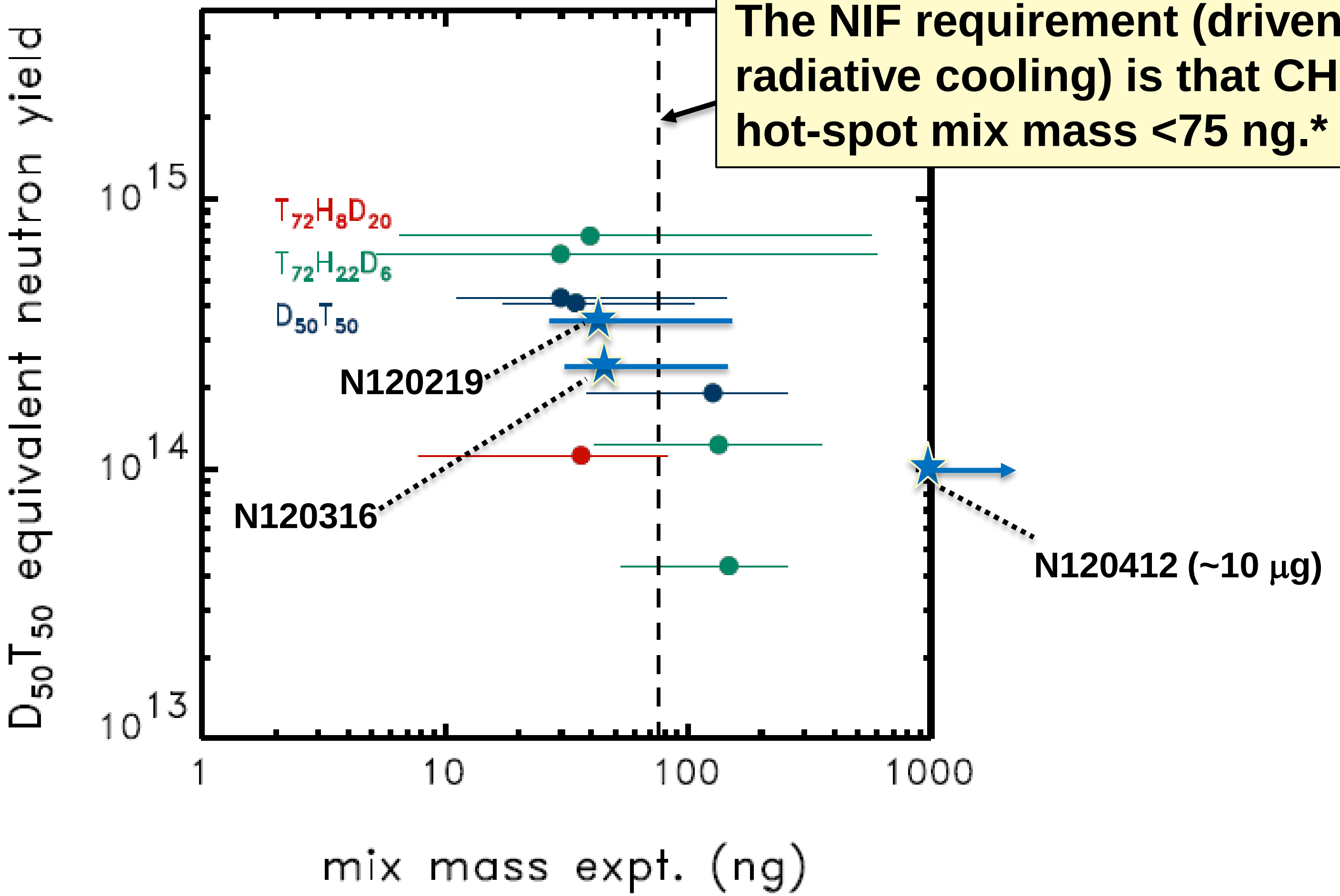
Supersnout II (5.75 to 16.5 keV)



X-ray radiography of imposed surface perturbations will be studied in future experimental campaigns

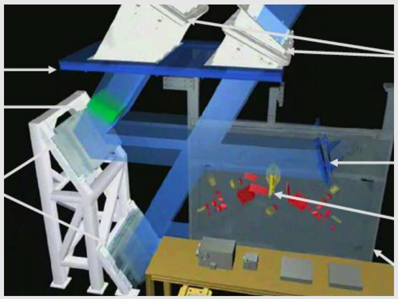
Large variations in the primary neutron yield are observed for comparable levels of hot-spot mix mass

The NIF requirement (driven by radiative cooling) is that CH(Ge) hot-spot mix mass <75 ng.*



Road map for the talk

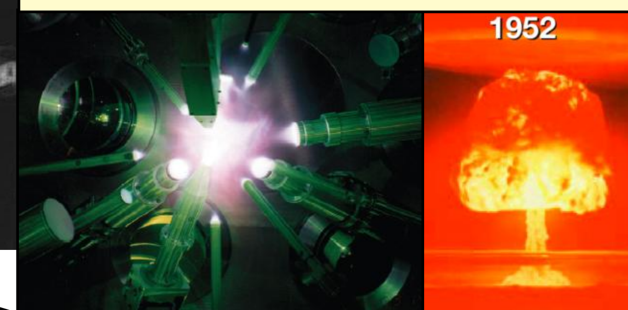
Hohlraum Energetics



FABS31 on NIF

Implosion phase

Assembly, burn phase



<u>How are we doing?</u>
-Good global measurements
-Beginning to see DT distribution
-Beginning to measure mix

Conclusion

- Excellent set of NIF Diagnostics – developed over many years

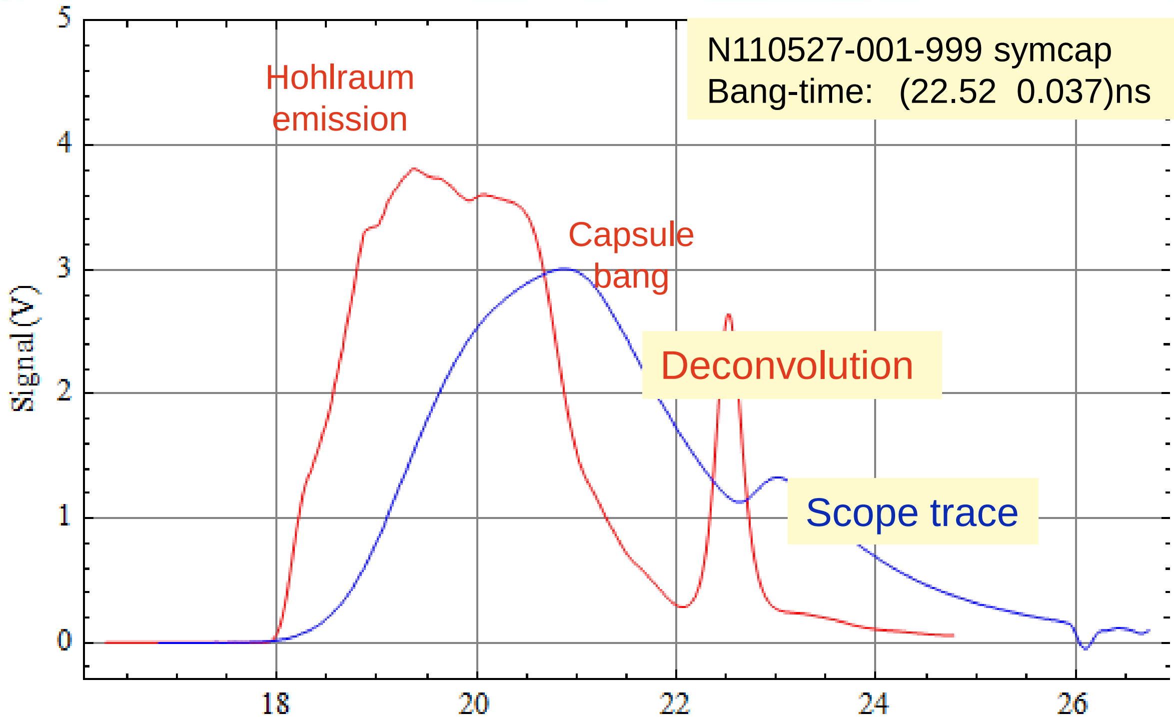
- A new generation of diagnostics is needed to more fully exploit NIF including:
  - ARC
  - Single LOS x-ray microscope
  - Gamma Spectrometer

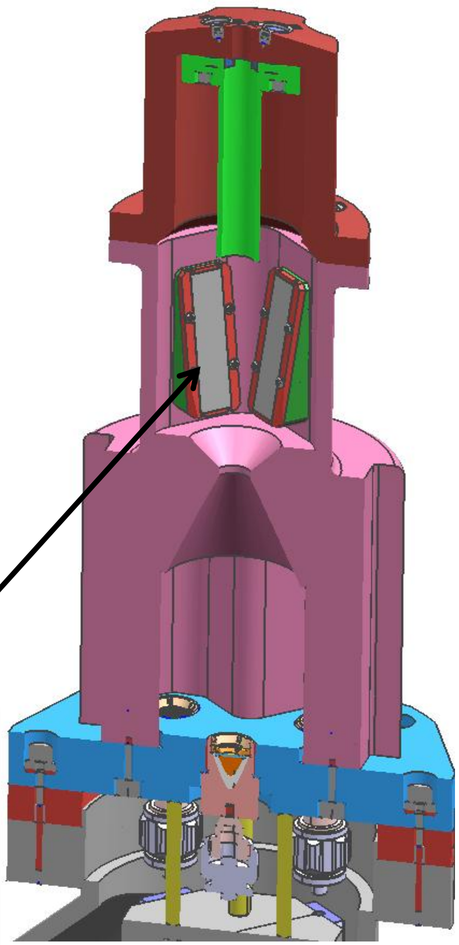
LOA (List of Acronyms)

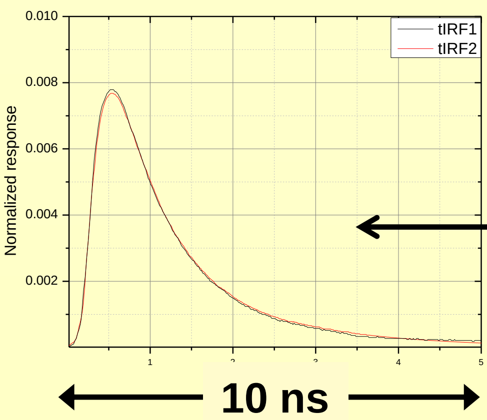
Acronyms	Description	Acronyms	Description
ARC	A Radiographic Capability (kJ-class short pulse laser)	NADS	Nuclear Activation Diagnostic (many flavors)
ARIANE	A Radiographic Capability (kJ-class short pulse laser)	NBI	Near Backscatter Imager (images light scattered around a beam cone)
BT	Bang Time (either from x-rays, g-rays or neutrons)	NIS	Neutron Imaging System
CGRO	Compton Gamma Ray Observatory	nTOF	neutron Time-of-Flight (neutron spectroscopy)
CR	Compton Radiography (imaging using x-rays ~ 100 keV)	OFVRC	High Resolution 2D Visar
DANTE	Trad	OISP	Optical Interferometer SHock Probe
DISC	DIM-Insertable Streak Camera	pTOF	proton Time-of-Flight
DIXI		RAGS	Radiochemistry And Gas Sampling
DSR	Down Scattered Ratio (#10-12MeV n's/#13-15MeV n's)	SCCal	Scattered Light Calorimetry
eHXI	Hard X-ray Imager	SOP	Streaked Optical Pyrometry (infer temperatures up to 10's keV)
FABS	Full Aperture Back Scatter (scattered light in the beam cone)	SPBT	South Pole Bang Time
FFLEX	Filter Fluorescer (time-integrated hard x-ray detector)	SpecE/SpecA	Spectroscopic nTOFs along an Equator LoS and in the Alcove
GOI	Gated Optical Imager	SPIDER	Streaked Polar Instrumentation for Diagnosing Energetic Radiation
GRH	Gamma Reaction History (bang-time/burn history DT g)	SRC	Solid RadioChemistry
GXD	Gated X-ray Detector (framing camera, <1E13 yield)	Supersnout	HSXRS combined with GXD/hGXI gated imaging
hGXI	Hardened Gated X-ray Imager (framing camera, <1E14 yield)	SXI	Static X-ray Imager (time-integrated x-ray pinhole camera)
HSXRS	Hot Spot X-Ray Spectrometer	SY	Switch Yard
LENS	Low Energy Neutron Spectroscopy (near future; En< few MeV)	VISAR	Velocity Interferometer for Any Reflector
MRS	Magnetic Recoil Spectrometer: measures r R from DSR	WRF	Wedged Range Filter (CR39-based proton spectrometer)
mVISAR	Multi-view VISAR		


NIF

SPBT measures capsule bang-time with <50 ps absolute accuracy







Crystal monochromator separates capsule signal from hohlraum background

Bang-time obtained by deconvolution using X-ray Impulse response measured on Comet as deconvolution kernel